Optimising ventilated package design for postharvest handling of pomegranate fruit in the cold chain

by

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Abstract

Packaging is an indispensable unit operation in handling and distribution of fresh fruit. Studies on postharvest handling of a number of horticultural products highlighted the importance of package design and knowledge of fruit and package thermophysical properties to effectively accomplish the precooling, cold storage, and refrigerated transport processes. However, the thermal properties of pomegranate fruit and its parts are unknown, and packages for postharvest handling of pomegranates have not been properly investigated. The aim of this study was to address the multi-parameter design requirements of ventilated packages for handling pomegranate fruit to ensure efficient cooling, high precooling throughput, reduction in packaging material used, and improved space utilization during cold storage and refrigerated transport.

Firstly, the thermal properties of whole fruit and the parts (epicarp, mesocarp, and arils) of early ('Acco') and late ('Wonderful') commercial pomegranate cultivars were determined experimentally using a transient heating probe. The values of thermal conductivity and diffusivity of both cultivars increased significantly with an increase in tissue temperature. The aril part was observed to have the highest thermal conductivity and specific heat capacity, respectively. For example, at 7 °C, the thermal conductivity (W m^{-1} K^{-1}) of 'Acco' was 0.419 ± 0.047, 0.352 ± 0.040, and 0.389 ± 0.030 for arils, mesocarp, and epicarp, respectively.

Next, a survey of the packaging used for pomegranate fruit in South Africa was conducted. Over 10 different corrugated fibreboard carton designs, with largely open tops, were found with different ventilations, ranging from 0.74–4.66% on bottom, to 0.71–5.33% on short (width), and 4.60–13.82% on the long (length) faces. The cartons were largely poorly ventilated on the short faces that leads to vent-hole misalignment and vent-hole blockage on pallet stacking which increases fruit cooling time and energy requirements.

Then, a virtual prototype approach based on computational fluid dynamics (CFD) was used to redesign the ventilation of one of the most commonly used pomegranate fruit cartons with intent to improved cooling performance. Fruit cooled in the new design had more uniform temperature distribution and significantly cooled faster (1.6 hours faster in fruit in polyliner) compared to fruit in the commercial design. This result highlights the need of proper carton vent design and vent-hole alignment in stacks.

Furthermore, a virtual prototype approach, based on CFD and computational solid dynamics (CSD) was used to design new ventilated corrugated paperboard cartons that hold pomegranate fruit in multilayers. Running virtual airflow and strength measurements enabled selecting the best alternatives, the 'Edgevent', and 'Midvent', which were then manufactured and evaluated for cold chain performance. The new designs improved fruit throughput by over 1.8 tonnes more fruit in a reefer compared to commercial single layer designs. For similar volume of fruit contained, the new designs saved over 31% cardboard material and an estimated equivalent of 11 trees per fully loaded 40-ft refrigerated container. Overall, the 'Midvent' performed best under cold chain conditions in terms of cooling efficiency and mechanical strength requirements. This warrants its commercialisation.

Lastly, the quality of fruit stored in 'Midvent' for 12 weeks under cold chain condition (7 ± 1 °C, 90% RH) and an additional 2 weeks at ambient (shelf life) condition (20 ± 1 °C, 65% RH) was compared with fruit in commercial carton under similar conditions. Fruit respiration followed a similar pattern in both carton designs marked by a 64% reduction after precooling. At the end of the shelf life period, fruit weight loss was 5.7% and 8.9% in the 'Midvent' and commercial design, respectively. Sensory attributes, decay incidence and colour changes were similar in new and commercial carton designs over the storage period.

Overall, research reported in this thesis has provided new data on thermophysical pomegranate fruit and has applied the virtual prototyping tool for horticultural packaging design. The new 'Midvent' carton design provides additional benefits in savings in packaging material, energy for fruit cooling, and bioresources efficiency. Future research should focus on performance test of this carton design in the commercial chain. New data on the thermal properties of pomegranate fruit provide needed input towards the modelling and prediction of fruit internal temperature profile during cooling processes.

Opsomming

Verpakking is 'n noodsaaklike eenheid in die hantering en verspreiding van vars vrugte. Studies oor na-oes hantering van 'n aantal tuinbouprodukte het die belangrikheid van pakketontwerp asook kennis rakende die termosfiese eienskappe van vrugte en verpakking beklemtoon. Dit is 'n manier om die voorverkoelings-, koelberging- en verkoelde vervoerproses effektief te bewerkstellig. Die termiese eienskappe van granate en die dele daarvan is onbekend, en pakkette vir die hantering van granate ná die oes is nog nie behoorlik ondersoek nie. Die doel van hierdie studie was om aandag te gee aan die ontwerp-vereistes van veelvuldige parameters van geventileerde verpakkings. Dit sluit in die doeltreffende verkoeling van granate om hoë voorverkoelings-deurset, vermindering van gebruikte verakkingsmateriaal, en verbeterde gebruik van die ruimte tydens verkoelde berging en vervoer te verseker.

Eerstens is die termiese eienskappe van heelvrugte en die vrugdele (epikarp, mesokarp en arillus) van vroeë ('Acco') en laat ('Wonderful') kommersiële granaat kultivars eksperimenteel bepaal met behulp van 'n oorgangs verhittingsensor. Die waardes van termiese-geleiding en diffusie van beide kultivars het aansienlik gestyg met 'n toename in weefsel temperatuur. Daar is waargeneem dat die arillus gedeelte onderskeidelik die hoogste termiese geleidingsvermoë en spesifieke hittekapasiteit gehad het. By 7 °C was die termiese geleidingsvermoë (W m^{-1} K^{-1}) van 'Acco' 0.419 ± 0.047, 0.352 ± 0.040 en 0.389 ± 0.030 onderskeidelik vir arillus, mesokarp en epikarp.

Vervolgens is 'n oorsig gedoen oor die verpakking wat vir granate in Suid-Afrika gebruik is. Meer as tien verskillende geriffelde veselbord kartonontwerpe, met grootliks oop bokante, is ondersoek, met verskillende ventilasies, wat wissel van 0.74–4.66% onderaan, tot 0.71–5.33% op kort (breedte) aansig en 4.60–13.82% op die lang (lengte) aansig, onderskeidelik. Die kartonne was grotendeels swak geventileer op die kort-aansigte, wat gelei het tot wanopstelling van die ventilasieopening asook die verstopping daarvan op die stapel van die palet. Dit verhoog dus die afkoeltyd en energiebehoeftes van die vrugte.

Daarna is 'n virtuele prototipe-benadering, gebaseer op berekeningsvloeidinamika (BVD) gebruik om die ventilasie van een van die mees gebruikte granaat kartonne te herontwerp, met die oog op verbeterde verkoeling. Vrugte wat in die nuwe ontwerp afgekoel is, het 'n meer eweredige temperatuurverspreiding gehad en vinniger afgekoel (1.6 uur vinniger in vrugte in 'polyliner') in vergelyking met vrugte in die kommersiële ontwerp. Hierdie resultaat

beklemtoon die behoefte aan behoorlike karton-opening ontwerp asook ventilasiegopening opstelling in stapels.

Verder is 'n virtuele prototipe benadering, gebaseer op BVD en berekeningssolieddinamika (BSD), gebruik om nuwe geventileerde geriffelde papierbord kartonne te maak, wat granate in meer lae kan verpak. Met die uitvoering van virtuele lugvloei- en sterktemetings is die beste alternatiewe, die 'Edgevent' en 'Midvent', gekies wat vervolgens vervaardig en geëvalueer is vir koue-ketting prestasies. Die nuwe ontwerpe het vrug-produksie oor 1.8 ton meer vrugte verbeter in 'n koeltrok, in vergelyking met kommersiële enkellaagontwerpe. Vir 'n soortgelyke hoeveelheid vrugte, het die nuwe ontwerpe meer as 31% kartonmateriaal bespaar met 'n geraamde ekwivalent van 11 bome per volgelaaide koelhouer van 40 voet. In die algemeen het die 'Midvent' die beste presteer onder koue-ketting toestande ten opsigte van verkoeling en meganiese sterktevereistes. Dit bevestig dus die kommersialisering daarvan.

Laastens is die kwaliteit van vrugte wat gedurende 'Midvent' in koue-ketting toestand gestoor is (7 ± 1 °C, 90% RH) asook 'n ekstra twee weke by die omgewingstoestand (rakleeftyd) (20 ± 1 °C, 65% RH) is onder soortgelyke toestande met vrugte in kommersiële kartonne vergelyk. Die respirasie van vrugte het 'n soortgelyke patroon in albei kartonontwerpe gevolg, met 'n afname van 64% na voorverkoeling. Aan die einde van die rakleeftydperk was die gewigsverlies van vrugte onderskeidelik 5.7% en 8.9% in die 'Midvent' en kommersiële ontwerp. Sensoriese eienskappe, verval voorkoms en kleurveranderings was dieselfde in nuwe en kommersiële kartonontwerpe gedurende die bergingstydperk.

Oor die algemeen het navorsing wat in hierdie proefskrif gerapporteer is, nuwe data oor die termofisiese eienskappe van granate verskaf, en is die virtuele prototiperings-instrument vir die ontwerp van tuinbouverpakkings toegepas. Die nuwe 'Midvent'-kartonontwerp hou ekstra besparings voordele in vir verpakkingsmateriaal, energie vir vrugteverkoeling en doeltreffendheid van biobronne. Toekomstige navorsing moet fokus op die prestasietoets van hierdie kartonontwerp in die kommersiële ketting. Nuwe data oor die termiese eienskappe van granate lewer die nodige insette vir die modellering en voorspelling van die interne temperatuurprofiel van vrugte tydens verkoeling.

This thesis is dedicated to my dear parents Mr. Remigius Mukungu and Mrs Margret Bavewo Mukungu

It always seems impossible until it's done (Nelson Rolihlahla Mandela).

Biographical sketch

Mr. Matia Mukama holds a Master of Science in Food Science from Stellenbosch University. He conducts research under the South African Research Chair (SARChI) in Postharvest Technology (since 2014), headed by Prof. Umezuruike Linus Opara. His research focusses on the application of engineering principles to improve the design of ventilated packaging used in the horticultural produce cold chain to reduce incidence of fruit postharvest losses and waste. From this work, he has published five peer-reviewed journal articles and five conference proceedings.

Mr. Mukama completed his BSc (Food Science and Technology) in May 2012 at Makerere University, Uganda. He then briefly worked with Uganda Tea Corporation as a Management Trainee, before being promoted to Assistant Manager Tea Operations, after 6 months following improvements in produced tea quality after strict implementation of manufacturing protocols, enforcement of good raw material quality ('green leaf') at reception, based on a "garbage-in garbage-out" principle, and training of workers. He then enrolled for MSc in Food Science at Stellenbosch University in 2014 in the SARChI Postharvest Technology Research Laboratory under the Intra-ACP Sharing Capacity to Build Capacity for Quality Graduate Training in Agriculture in African Universities (SHARE). In August 2016, he enrolled for PhD in Food Science under the same Lab.

Matia is also passionate about Science communication and recently (Feb 2019) won the Fame Lab Science Communication and Public Speaking Competition, Stellenbosch University heat. He further emerged 1st Runners-up in the National Fame Lab Science Communication and Public Speaking Competition, South Africa, in May 2019. He is a professional member of the South African Association for Food Science and Technology (SAAFoST) and South African Council for Natural Scientific Professions (SACNASP).

His career goal is to contribute to Science and technological innovations applicable to food value addition, wastage reduction, improved human nutrition, and overall food security. Mr. Mukama also enjoys dancing, soccer, travelling, and adventure.

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Preface

This thesis is a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters has, therefore, been unavoidable. Language and styles used in this thesis are in accordance with the requirements of the International Journal of Food Science and Technology.

List of contributions

1) *Publications–Peer reviewed journal paper*

Mukama, M., Ambaw, A. & Opara, U.L. (2020). A virtual prototyping approach for redesigning the vent-holes of packaging for handling pomegranate fruit – A short communication. *Journal of Food Engineering*, **270**, 109762.

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Thermal properties of whole and tissue parts of pomegranate (*Punica granatum*) fruit. *Journal of Food Measurement and Characterization*, **13**(2), 901-910.

2) *Publications–Peer reviewed conference proceedings*

Mukama, M., Ambaw, A. & Opara, U.L. (2018). Analysis of the thermal and bio-physical properties of pomegranate fruit. *Acta Horticulturae*, **1201**, 273-280.

3) *Conference–Posters/Presentations*

Mukama, M., Ambaw, A. & Opara, U.L. (2018). Some engineering properties of pomegranate fruit relevant to postharvest handling and processing. 12th International Commission of Agricultural and Biosystems Engineering (CIGR) Section VI Technical Symposium. International Institute of Tropical Agriculture, Ibadan, Nigeria, 22–25 October.

Mukama, M., Ambaw, A. & Opara, U.L. (2017). Analysis of the thermal and biophysical properties of pomegranate fruit. VII International Conference on Managing Quality in Chains (MQUIC). Stellenbosch University, South Africa, 4–7 September.

4) *Articles under review*

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Thermophysical properties of fruit–a review with reference to postharvest handling. *Journal of Food Measurement and Characterization.*

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Advances in design and performance evaluation of fresh fruit packaging: A review. *Food Packaging and Shelf Life.*

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Characterisation of ventilated multi-scale packaging used in the pomegranate industry in South Africa. *Agricultural Mechanization in Asia, Africa and Latin America.*

Table of contents

Chapter 1

General introduction

Pomegranate fruit production and demand is on the rise world over given the health promoting benefits associated with the fruit consumption. Thus far, increased global consumption of the fruit has been linked to anti-hypertensive, anti-mutagenic, and anti-cancer benefits that trace back to phytochemical, antioxidant, and radical scavenging properties of pomegranate fruit components (Aviram *et al*., 2008; Fawole & Opara, 2012; Opara *et al*., 2017). The total world production is currently estimated at 3 million tons per year (Erkan & Dogan, 2018). In South Africa, the local market consumption is on the rise, reaching 376 tons in 2018, while total exports was 1.2 million 3.8 kg equivalent cartons, with a projected 1.4 million 4.3 kg equivalent cartons of fruit pack out by 2023 (POMASA, 2019). However, pomegranate fruit is susceptible to excessive moisture loss, fungal infection, bruising, and decay if the fruit is not properly handled, packaged, and stored after harvest (Kader, 2006; Caleb *et al*., 2012; Munhuweyi *et al*., 2016). Packaging and cold chain handling help preserve fruit quality for extended periods. Pomegranate shelf life can be prolonged up to 4 months if fruit is kept at temperature and relative humidity (RH) between 5 °C to 8 °C and 90% to 95%, respectively (Kader, 2006; Arendse *et al*., 2014).

The global packaging market value is estimated to reach US$ 1 trillion by 2021 with an annual growth rate of 5–7% until the end of the decade (Smithers, 2019). Food packaging accounts for over 35% of this global packaging industry in the developed markets and further growth is projected in the developing world markets with higher population growth (Rundh, 2005). Packaging is essential for successful food marketing and logistics in addition to its primary role of product protection. Paper, corrugated board, and other paperboard package materials account for one-third of the global packaging trade (Rundh, 2005; Opara & Mditshwa, 2013; GADV, 2019). Packaging used in the fresh fruit industry requires ventilation through which respiration and metabolic heat is removed from the fruit environment in the cold chain process (Berry *et al*. 2015). The design of the vent-holes (area, number, position) affect the carton strength and cooling properties of the fruit therein (Pathare *et al*., 2012; Fadiji *et al*., 2016; Berry *et al*., 2017; Mukama *et al*., 2017). For corrugated fibreboard cartons, increase in vent area compromises the carton strength (Fadiji *et al*., 2016) although this may improve fruit cooling rates. The design process of such cartons is thus normally a trade-off between achieving structural integrity, adequate and fast cooling, and economics.

Fruit cold chain management is an interplay of the magnitude and uniformity of the cooling airflow, fruit properties, package design, and stack configurations (Berry *et al*., 2016). The cold chain processes during postharvest handling involve creating chilled air at the optimum storage temperature using a refrigeration system and maintaining uniform circulation of the chilled air through and around the stack of produce by using air circulation units both during storage and transportation. In fruit postharvest handling, the cold chain is widely initiated using forced air cooling, where fruit temperature is brought down to the recommended storage temperature in the shortest time possible using powerful fans that force the chilled air over produce inside ventilated cartons. The sizing, selection and operation of the refrigeration and air circulation systems requires knowledge of the thermophysical properties of the produce, the packaging, temperature and humidity of the surrounding air (Zhu *et al*., 2008; Huang & Liu, 2009; Lozano, 2009). There has been renewed global interest in the development of cold-chain management systems, including ventilated packaging aimed at reducing postharvest losses, energy usage, and the carbon footprint (Opara, 2010). The energy cost of refrigeration and to operate fans and blowers that drive cold air through stacked produce is profoundly affected by the packaging design. Attempts to enhance the energy performance of cold-chain processes through packaging design has shown significant potential (Defraeye *et al*., 2014; Ambaw *et al*., 2017; Mukama *et al*., 2017).

Thermophysical properties characterize the rate and degree of heat exchange between produce and its surrounding. Thermophysical data is a prerequisite for predicting heating or cooling rates and to estimate heating or cooling loads of thermal processes. Hence, knowledge of the thermophysical properties of food material is vital for the design and implementation of handling, processing, and preservation processes (Singh, 2006; Carson *et al*., 2016). The most important thermal properties that influence process and system design are the specific heat, thermal conductivity, and thermal diffusivity (Mohsenin, 1980; Sweat, 1994). Heat conduction, between fruit to fruit or convection from cooling air to fruit during cooling is governed by the thermal conductivity, specific heat capacity, and thermal diffusivity of the fruit, packaging materials, and the cooling medium (Lu *et al*., 2007; Zhu *et al*., 2008). Fruit being biological materials undergo complex enzymatic and physiological changes in their postharvest life (Aremu & Fadele, 2010; Modi *et al*., 2013). These alter their composition and properties in time. Many studies assumed fruit as a homogeneous solid system with effective thermal properties. However, thermophysical properties of the different parts of a fruit are crucial for the detailed investigation of the spatiotemporal temperature distribution inside the fruit. Literature on thermophysical data of pomegranate fruit or its parts is lacking.

There is effort towards reduction in time and costs required in new product design and developments (Zorriassatine *et al*., 2003; Gibson *et al*., 2004; Huang *et al*., 2007). The continuous growth in computer power has eased such developments through the use of virtual prototyping and testing, before production of physical prototypes (Gibson *et al*., 2004). Virtual prototyping involves creation of precise virtual models and scenarios in the conceptualisation process, envisaging real circumstances which are then transformed into physical processes after rigorous and satisfactory virtual performance (Huang *et al*., 2007). The complexity of air movement inside stacks of cartons and around individual fruit makes experimental measurements and information of local airflow, heat, and mass transfer very difficult, time consuming and challenging. The virtual prototyping design approach was pioneered in the automotive and aerospace industries (Zorriassatine *et al*., 2003), but is used currently across sectors including construction, and even in the field of postharvest packaging (Wu *et al*., 2019). The major virtual technologies in use in postharvest research and innovation include computational fluid dynamics (CFD), computational thermal dynamics (CTD), and computational solid dynamics (CSD). These tools allow creation of models that permit exact control of operating parameters while providing vital information like the airflow, mechanical stress, mechanical strain, and temperature patterns within the stack of fruit under refrigeration conditions, and thus, provide mechanisms and performance details of the processes (O'Sullivan *et al*., 2016; Fadiji *et al*., 2018; Wu *et al*., 2019). Package design and evaluation should employ a multiparameter approach giving a holistic assessment of all functionalities and parameters to help avoid contradictions in the design requirements. For example, increasing the ventilation area to improve cooling rates without consideration of the carton strength may result in a carton lacking in mechanical integrity, increasing chances of fruit mechanical damage. Effective space utilisation and fruit packing density in cold rooms and reefers is also an important carton design consideration, especially during peak produce season and shipping to long distant markets.

The discussion above highlights the dynamics of fruit packaging and cold chain operations. Previous studies on postharvest handling of a number of horticultural products such as apples (Zou *et al*., 2006a, b; Opara & Zou, 2007; Delele *et al*., 2013a, b; Berry *et al*., 2016, 2017; Fadiji *et al*., 2016, 2018, 2019), citrus (Defraeye *et al.*, 2013, 2014), table grape (Ngocobo *et al.*, 2013) and strawberry (Ferrua & Singh, 2009a, b) highlighted the importance of package design to effectively accomplish the precooling, cold storage and refrigerated transport processes. However, packages for postharvest handling of pomegranates have not been properly investigated. Preliminary studies showed that two different carton designs currently used for handling pomegranate fruit had significantly different produce cooling rates, cooling uniformities and energy usage during a precooling process (Ambaw *et al.*, 2017; Mukama *et al.*, 2017). The authors suggested the need to optimize the package designs with respect to airflow resistance, cooling rate, cooling uniformity, energy usage, space utilization, and throughput. The aim of this research was a practical one: to design new ventilated packages to ensure energy and resource efficiency, high precooling process throughput, and efficient space utilization during cold storage and refrigerated transport of pomegranate fruit.

In order to achieve this aim, the specific objectives were to:

1) Determine the thermal properties of pomegranate fruit relevant to packaging and cold storage,
2) Characterise ventilated multi-scale packaging used in the pomegranate industry in South Africa,
3) Redesign the vent-holes of pomegranate fruit packaging using a virtual prototyping approach,
4) Investigate the potential for multi-layer ventilated packaging of pomegranate for optimum space utilisation during storage and refrigerated transport, and
5) Assess the quality of pomegranate fruit handled in the developed package designs during and at the end of the storage period.

Thesis structure

This thesis is divided in two sections. Section A includes a review of literature on thermophysical properties of fruit, and determination of thermal properties of pomegranate fruit relevant to packaging and cold storage. Section B includes a review of literature on design and performance of ventilated packaging, and then a description of the design process and analysis of new ventilated corrugated pomegranate fruit packaging. A generalised study design approach employed in this thesis is shown in Fig. 1.1.

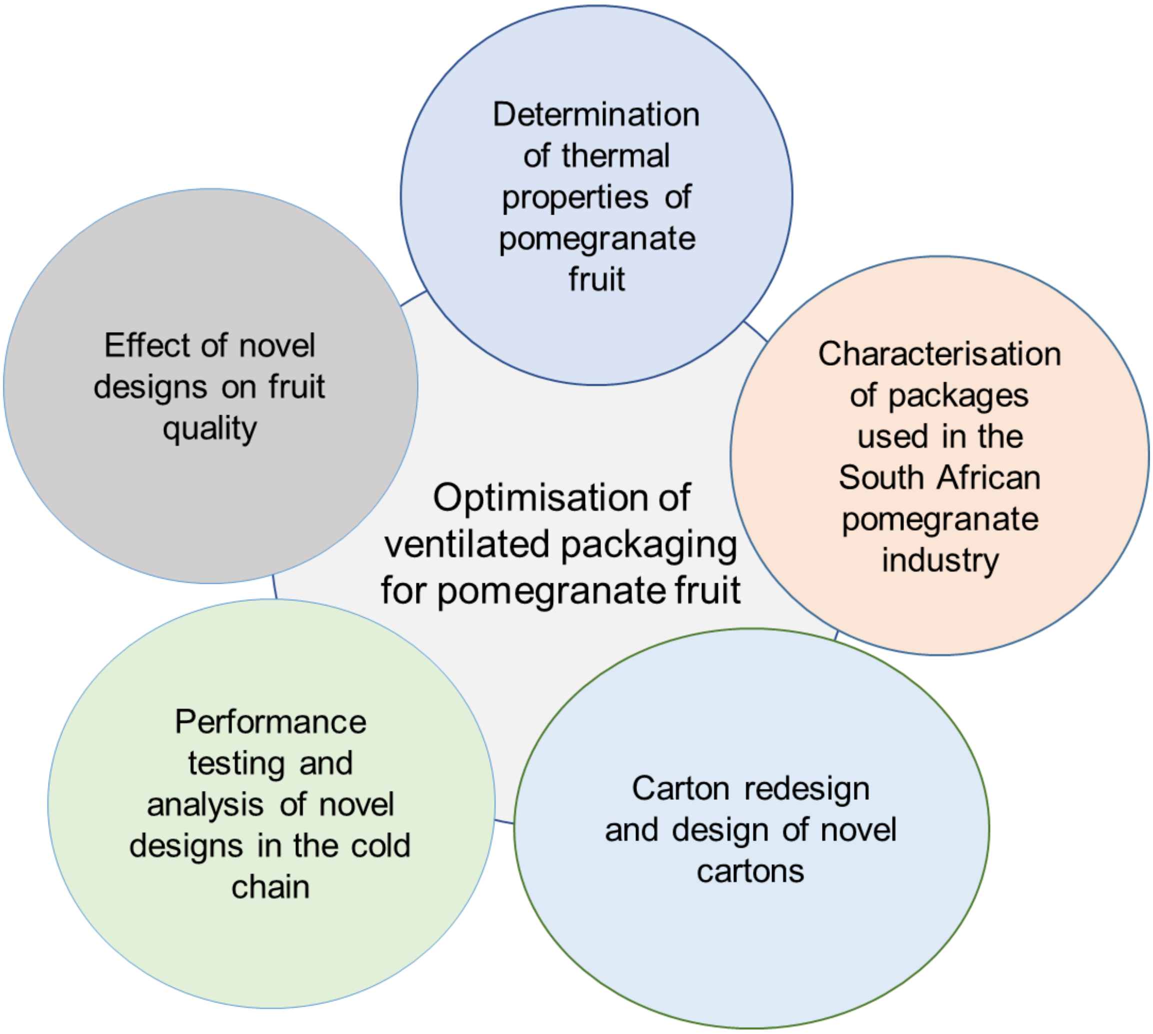

Fig. 1.1 Generalised study design in this thesis.

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Section A

Declaration by the candidate

With regard to Chapter 2, pages 13–62, the nature and scope of my contribution were as follows:

Nature of contribution	**Extent of contribution (%)**
Compiled and edited manuscript in its entirety throughout the publication process	80

The following co-authors have contributed to Chapter 2, pages 13–62:

Name	**e-mail address**	**Nature of contribution**	**Extent of contribution (%)**
Alemayehu Ambaw	tsige@sun.ac.za	Contributed to the formulation of the review of the review and editing the document in its entirety throughout the publication process	10
Umezuruike Linus Opara	opara@sun.ac.za	Conceptualised the review and and edited the document in its entirety throughout the publication process	10

Declaration with signature in possession of candidate and supervisor **Signature of candidate**	16/08/2019 **Date**

Declaration by co-authors

The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 2, pages 13–62,

2. no other authors contributed to Chapter 2, pages 13–62 besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2, pages 13–62 of this dissertation.

Signature	**Institutional affiliation**	**Date**
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019

Chapter 2

Thermophysical properties of fruit – a review with reference to postharvest handling

Abstract

The thermophysical data of fruit is vital to the study and optimization of postharvest handling processes. However, data available in the literature are not always consistent and must not be used directly. It is crucial to examine the accuracy and reliability of the property data. Also, models to predict the thermal properties of fruit are not distinctly identified and included in the list of models for food materials. The aim of this review was to show the gaps in fruit properties data with emphasis on those properties that are important during postharvest handling. This paper also presents a review of the measurement and prediction techniques for the thermophysical properties of fruit. Fruit thermophysical properties vary with temperature, moisture content, cultivar, and even between the various parts of the same product. The presented review is a valuable input for developing mathematical models that predict cooling rate, cooling time, cooling uniformity and refrigeration energy usage during postharvest handling processes (e.g. precooling and cold storage), as well as for applications related to prediction and monitoring of temperature induced fruit quality changes.

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*Under review:

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Thermophysical properties of fruit–a review with reference to postharvest handling. *Journal of Food Measurement and Characterization*

2.1. Introduction

Fruits are seasonal and have limited shelf life before senescence and associated losses. A common postharvest challenge is to prolong the shelf life of perishable commodities for the fresh market. This is achieved through strict control of environmental conditions (airflow, temperature, humidity) and gas composition in the atmosphere during postharvest handling. This includes rapid cooling of the produce immediately after harvest and control of temperature and humidity during storage, transportation and at the retail display (Mukama *et al*., 2018a, 2019a). Cooling of produce reduces the respiration, enzymatic activities, the growth, and proliferation of microorganisms, thus retarding deterioration. The control strategies are governed by the thermophysical properties of the produce, the ambient condition and the associated packaging and handling accessories (Zhu *et al*., 2008; Huang & Liu, 2009; Lozano, 2009; Carson *et al*., 2016). Understanding the rate and degree of heat and moisture exchange between the produce and its surroundings is crucial to achieve the desired quality, shelf life, and market price.

The cold chain processes during postharvest handling involve creating chilled air at the optimum storage temperature using a refrigeration system and maintaining uniform circulation of the chilled air through and around the stack of produce by using air circulation units. The sizing, selection, and operation of the refrigeration and air circulation systems requires knowledge of the thermophysical properties of the produce, the packaging, temperature, and humidity of the surrounding air (Zou *et al*., 2006a, b; Zhu *et al*., 2008; Huang & Liu, 2009; Lozano, 2009). Mathematical models are frequently used to study the cooling rate, cooling uniformity, and energy usages of precooling, cold storage, and refrigerated transport of produce. The reliability of these models are dependent on the accuracy of the thermophysical data (Opara & Zou, 2007; Ferrua & Singh, 2009; Dehghannya *et al*., 2010, 2011, 2012; Ambaw *et al*., 2013, 2017, 2018; Berry *et al*., 2016, 2017).

The main thermophysical properties relevant for modelling and analysis of thermal postharvest processes are thermal conductivity (k), thermal diffusivity (α) and specific heat capacity (C_p) of the cooling medium (which is usually air), the produce and the packaging material. These values are interrelated as $C_p = k/\rho\alpha$, where ρ is the density of the material. Thermal properties of materials involve parameters associated with the three modes of heat transfer: radiation, conduction, and convection. Radiation is the transfer of heat through electromagnetic waves. This form of heat transfer is crucial before harvest when fruit is hanging on the tree. Radiant waves from direct sunlight during the summer months can result in sunburn damage and losses due to sunburn damage is a major source of economic loss in the marketing fresh fruit due to fruit discolouration and variability in texture (Li *et al*., 2014). Conduction is the movement of heat to or from the produce due to temperature gradient. In fruit, like all materials, conduction of heat is dependent on the produce thermal conductivity which is also affected by factors like the fruit moisture content and porosity (Lu *et al*., 2007; Zhu *et al*., 2008). Convection involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). In postharvest handling of produce, the bulk fluid is usually chilling air from the refrigeration unit. In hydro cooling cases, it is chilled water. The chilling air is forced to flow through and around the stacked produce to extract the excess heat from the produce and circulate back to the refrigeration unit to reject the extracted heat (Wang *et al*., 2001; Mukama *et al*., 2017).

Thermal operations in the postharvest deals with living materials characterised by properties with strong spatial and temporal variability (Hertog *et al*., 2007). During processing, the thermal properties of these materials change in time and space depending on the composition, the physical structure of the food, and the ambient condition (Fikiin & Fikiin, 1999; Figura & Teixeira, 2007; Sahin & Sumnu, 2006). For instance, for stone fruit like plums, there could be significant property differences between the seed and the flesh parts of the fruit. It is important to know the cooling history of the flesh part, the stone part, and the stone-flesh interface to accurately model the heat transfer phenomena. If the seed part is prominent, it plays a significant role in the moisture and heat transfer process (Cuesta & Alvarez, 2017). Hence, the error incorporated in models that uses a single average or effective property value could be significant (de Moura *et al*., 1998).

In this paper, a review of the thermophysical properties of fruit relevant to postharvest handling are presented and discussed, including an overview of the thermal treatments applied to maintain quality. In addition, recent advances in the measurement and prediction of fruit thermophysical properties are highlighted.

2.2. Thermal treatments for postharvest handling of fruit

Thermal processing involves transfer of heat energy to or from a product. Table 2.1 summarizes some of the most common thermal treatment processes during postharvest handling of fruit. Precooling is the quick removal of the field heat shortly after the harvest of a crop. Different methods of precooling are available, including room cooling, forced air cooling, vacuum cooling, hydro cooling or spray cooling and package icing. Among these, forced air cooling (FAC) is the most favoured cooling technique (Brosnan & Sun, 2001; Dehghannya *et al*., 2010). Fruit for distant markets should be kept cool and at the optimum condition during transportation. Refrigerated containers (reefers) are the most used means of transporting fresh produce to distant markets. Reefers are designed to distribute chilled air from the floor, via specific T-shaped decking. The air delivery system should be powerful enough to ensure enough and uniform flow of air through the stacked produce inside the shipment (Getahun *et al*., 2017a, b).

Refrigerated storage room is used to keep the quality of produce beyond their normal shelf life. Chilled air is constantly circulated through the stack by use of air driving equipment and heat is removed from the produce and other sources by the refrigeration/cooling unit. In addition, cold storage rooms are occasionally used for additional treatments like gassing and fungicide applications (Delele *et al*., 2012; Ambaw *et al*., 2014). As in the precooling process, the effectiveness of the air distribution, heat exchange and energy usage of the storage operation are affected by the design of packaging boxes and their stacking patterns in the room. Non-uniform flow of air inside the cool store could cause uneven cooling leading to loss of product quality.

Retail (display) cooling systems minimizes radiation and other sources of heat during sales in stores and supermarkets. While keeping the produce cool, display coolers should allow good visibility and ensure free access to stored food for shop customers. This is accomplished by an insulation barrier called air-curtain developed by recirculating air from the top to the bottom of the display structure. The air curtain is a non-physical barrier between chilly air inside the case and the warm shop environment. The modelling and thermal analysis of the air curtains is required to assess the effect of air circulation in front of the cabinet and the disturbance created by the consumers taking food from the shelves (Ge & Tassou, 2001; Chaomuang *et al*., 2017; Rosca *et al*., 2017).

2.2.1. Modelling the thermal processes in the postharvest

The modelling of the thermal processes in the postharvest is based on the mathematical statement of the conservation laws (conservation of mass, momentum and energy). The continuity Eq. (2.1) and Reynolds-averaged Navier-Stokes (RANS) Eq. (2.2) are the basic mathematical formulations that govern the motion of the cooling fluid.

$$\nabla \cdot \mathbf{U} \quad = \quad 0 \tag{2.1}$$

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot (\mathbf{U} \otimes \mathbf{U}) - \nabla \cdot \left(\left(\frac{\mu + \mu_t}{\rho_a} \right) \nabla \mathbf{U} \right) - S_U + \frac{1}{\rho_a} \nabla p = 0 \tag{2.2}$$

The spatiotemporal distribution of the air temperature and the produce temperature are estimated using additional Eq. (2.3) and Eq. (2.4)

$$(\rho_a C_{pa}) \left(\frac{\partial T_a}{\partial t} + \mathbf{U} \cdot \nabla T_a \right) = \nabla \cdot ((k_a + k_t) \nabla T_a) + h_{pa} (T_p - T_a) \tag{2.3}$$

$$(\rho_p C_{pp}) \frac{\partial T_p}{\partial t} = \nabla \cdot (k_p \nabla T_p) + h_{pa} (T_a - T_p) + Q_r - Q_v \tag{2.4}$$

Table 2.2 summarizes the symbols and thermophysical property data required corresponding to the model Eq. (2.1) to (2.4).

Due to the complexity and size-scale of a fully loaded cold storage room and a reefer container, mathematical modelling of these systems is computationally difficult. To this end, the method of volume averaging is employed. This approach assumes the stack as a porous medium and eliminates the complex geometry of stacked packaging systems (Zou *et al*., 2006a, b). This considerably simplifies the geometry discretization (meshing) step and the subsequent computation. The porous medium approach is obtained by modifying Eq. (2.3) and Eq. (2.4) (Nield & Bejan, 2013; Ambaw *et al*., 2013, 2017). Taking averages over an elemental volume of the medium we have, for the solid phase, Eq. (2.5):

$$(1-\varphi)(\rho C)_S \frac{\partial T_s}{\partial t} = (1-\varphi)\nabla.(k_s \nabla T_s) + (1-\varphi) q_s''' \tag{2.5}$$

and, for the fluid phase, Eq. (2.6):

$$\varphi (\rho C_p)_f \frac{\partial T_f}{\partial t} + (\rho C_p)_f v.\nabla T_f = \varphi \nabla.(k_f \nabla T_f) + \varphi q_f''' \tag{2.6}$$

The subscripts *s* and *f* refer to the solid and fluid (air in this case) phases, respectively, *C* is the specific heat of the solid, φ is the porosity of the stack, *v* is the volume of the fluid, C_p is the specific heat at constant pressure of the fluid, *k* is the thermal conductivity, and q''' is the heat production per unit volume (W m^{-3}) (Nield & Bejan, 2013). Hence, additionally, properties like porosity and airflow resistances of the porous domain are incorporated for the purpose of applying the porous medium approach. These two additional properties are the properties of the stack determined by the shape, size and stacking of the produce, the packaging design, and orientation (Verboven *et al*., 2006; Delele *et al*., 2009; Ambaw *et al*., 2013).

Table 2.1 Thermal treatments in postharvest handling of fruit

Thermal treatment	**Examples**	**Mode of action**	**Reference(s)**
Cold treatment	Precooling	Fruit temperature is brought down to the recommended storage temperature in the shortest time possible to reduce detrimental fruit physiological and biological changes. Methods used include hydro cooling, forced air cooling etc.	Ravindra & Goswami, (2008), Ambaw *et al*., (2017), Mukama *et al*. (2017)
	Refrigerated transport	Fruit are transported in reefers that are maintained at recommended temperature and relative humidity of particular fruit. Aim is to minimise detrimental physiological and biological changes in fresh fruit.	Tanner & Amos, (2003), Defraeye *et al*. (2016) Getahun *et al*. (2017a, b)
	Refrigerated storage	Fruit are kept in a room maintained at the recommended temperature and relative humidity for a particular fruit. Aim is to minimise detrimental physiological and biological changes in fresh fruit.	Kader, (2006), Delele *et al*. (2009), Ngcobo *et al*. (2013), Ambaw *et al*. (2014)
	Refrigerated retail display	Fruit are displayed in cabinets on shelves maintained at the recommended temperature and relative humidity conditions. Aim is to minimise detrimental physiological and biological changes in fresh fruit.	Ge & Tassou (2001), Nunes *et al*. (2009), Kou *et al*. (2015), Chaomuang *et al*. (2017), Rosca *et al*. (2017)
Heat treatment	Hot air treatment	Hot air between 35°C–39 °C is blown onto the fruit. Helps control insects, prevent fungal development, reduces chilling injury in citrus, increases sugar levels, decrease polyphenol oxidase action, increase in stress proteins, etc.	Perotti *et al*. (2011), Lauxmann *et al*. (2014), Lurie & Pedreschi, (2014), Yanclo *et al*. (2018)
	Hot water treatment	Fruit is dipped in water at varying temperatures for varying times up to 63 °C for less than one minute. This may trigger increase in sugars and fatty acids, increase flavonoids, induce defence cell and structure proteins, etc.	Zhang *et al*. (2011), Yun *et al*. (2013), Lurie & Pedreschi, (2014), Yanclo *et al*. (2018)
	Intermittent warming	Intermittent warming is the periodic exposure of fruit under cold storage to short warming cycles. Reduces fungal proliferation and chilling injury in some fruit	Artes *et al*. (2000), Fergusson *et al*. (2000), Fallik, (2004), Yanclo *et al*. (2018)

Table 2.2 Properties in the Reynolds-averaged Navier-Stokes equations

Property	Description	Unit
μ	the dynamic viscosity of air	kg m^{-1} s^{-1}
μ_t	Turbulent viscosity of air	kg m^{-1} s^{-1}
C_{pa}	heat capacity of air	J kg^{-1} K^{-1}
ρ_a	density of air	kg m^{-3}
k_{a0}	thermal conductivity of air	W m^{-1} K^{-1}
C_{pp}	heat capacity of the produce	J kg^{-1} K^{-1}
ρ_p	density of the produce	kg m^{-3}
k_p	thermal conductivity of the produce	W m^{-1} K^{-1}
k_t	turbulent thermal conductivity	W m^{-1} K^{-1}
h_{pa}	convective heat transfer coefficient	Wm^{-2} K^{-1}
T_p	Temperature of produce	K
T_a	Temperature of air	K
U	Velocity	m s^{-1}
T	Time	s
P	Pressure	Pa
S_u	Momentum source term	m s^{-2}

2.3. Thermophysical properties of fruit

The heat exchange between a fruit and its surrounding depends on the thermal properties of the fruit and the surrounding cooling medium. The most important properties to analyse thermal processes are thermal conductivity, thermal diffusivity, specific heat and density of the produce, packaging materials and the cooling medium (Mohsenin, 1980; Choi, 1985; Sweat, 1994; Kumar *et al*., 2008; Lozano, 2006, 2009; Gulati & Datta, 2013). In addition, the respiration and transpiration properties and the accompanying heat and moisture generations during storage of fruit are crucial to design and optimize thermal processes in the postharvest.

The thermal properties of the cooling medium (air) and most packaging materials are well established and can be effortlessly obtained from literature. On the other hand, produce, being biological materials, have thermal properties that vary in time, temperature and moisture content (Table 2.3). The absence of any consistent trend is apparent in Table 2.3. This signifies the caution required when using literature data in prediction models. Also, there may be considerable difference between fruit parts. This is especially important for fruit containing prominent stony core surrounded by fleshy or pulp tissue, such as mangoes, cherries and plums

(Cuesta & Alvarez, 2017). The ligneous core—the seed has radically different physical and may thus have thermal parameters different from those of the edible part, the pulp. In a study on the thermal properties of pomegranate fruit, Mukama *et al*. (2019b) found that the aril part of the fruit recorded higher values of specific heat capacity and thermal conductivity compared to the mesocarp and peel, while the peel had the lowest density.

2.3.1. Specific heat capacity of fruit

The specific heat capacity (C_p) of a material determines the amount of heat needed to raise the temperature of one kilogram of mass by 1 Kelvin (Juliano *et al*., 2011). Specific heat values of whole fruit ranged from 1.72–4.05 kJ kg^{-1} K^{-1} with an average value of 3.74 kJ kg^{-1} K^{-1}. Fruit with high water content generally have higher specific heats. For example, melons have average specific heat capacity of 4.05 kJ kg^{-1} K^{-1} (Ikegwu & Ekwu, 2009).

Specific heat values have been reported to increase with an increase in fruit moisture content. A similar trend is reported with regards to temperature (Laohasongkram *et al*., 1995; Aghbashlo *et al*., 2008; Juliano *et al*., 2011; Mercali *et al*., 2011; Zabalaga *et al*., 2016). The effect of moisture content has however shown to be strong compared to temperature (Aghbashlo *et al*., 2008; Oliveira *et al*., 2012). Kumar *et al*. (2008) reported a linear increase of specific heat of tomatoes with temperature ranging from 30 °C to 130 °C, just like Aghbashlo *et al*. (2008) for berberis between 50 °C and 70 °C 1.97–3.28 kJ kg^{-1} K^{-1}. On the other hand, Singh *et al*. (2009) reported negligible effect of temperature on the specific heat of unfrozen food products. Different cultivars of the same fruit may also have different specific heat values. For instance, at 40 °C, 50% moisture content, Golden Delicious, Idared, Jonagold and Jonathan apple cultivars had specific heat capacity of 3.22 kJ kg^{-1} K^{-1}, 3.04 kJ kg^{-1} K^{-1}, 2.82 kJ kg^{-1} K^{-1}, and 2.42 kJ kg^{-1} K^{-1}, respectively (Lisowa *et al*., 2002). This is linked to difference in fruit material composition and microstructure (Mohsenin, 1980).

Table 2.3 Thermal properties of different horticultural fruit from literature

Category	Fruit type	Temp (°C)	Moisture content (%)	Density, ρ (kg m^{-3})	Thermal diffusivity, α (x 10^{-7} m^2 s^{-1})	Specific heat capacity, C_p (kJ kg^{-1} K^{-1})	Thermal conductivity, k (W m^{-1} K^{-1})	Reference(s)
Pomes	Apple	30	-	813	1.36	3.81	0.42	Martínez-Monzó *et al*. (2000)
	Apple	40	-	813	1.51	3.86	0.48	Martínez-Monzó *et al*. (2000)
	Apple	50	-	813	1.72	3.85	0.54	Martínez-Monzó *et al*. (2000)
	Apple	40	88	-	1.78	-	0.54	Jljasowa *et al*. (1987)
	Apple	6–28	-	-	0.88–1.19	-	0.404–0.423	Bozikova (2007)
	Apple	0-30	85	-	1.37	-	-	Singh (1982)
	Apple	40	88	-	-	3.83	-	Ratti & Mujumdar (1993)
	Apple (green)	28	88.5	790	-	-	0.422	Sweat (1974)
	Apple (red)	28	84.9	840	-	-	0.513	Sweat (1974)
	Apple (red)	0–30	85	840	1.4	-	-	Bennet *et al*. (1969)
	Apple (grated)	6–28	-	-	1.28–1.38	-	0.553–0.575	Bozikova (2007)
	Apple (juice)	6–28	-	-	1.43–1.47	-	0.660–0.642	Bozikova (2007)
	Pear	28	86.8	1000	-	-	0.595	Sweat (1974)
	Pear	-	-	990	-	-	0.543	Liang *et al*. (1999)
	Pear (bartlet)	-	83.8	-	-	3.73	-	Sweat (1994)
Berries	Strawberry	28	88.8	900	-	-	0.462	Sweat (1974)
	Strawberry	5	92	-	1.27	-	-	Singh (1982)
	Straw berry jam	20	41	-	1.2	-	-	Sweat (1985)

Table 2.3 *Continued*

Category	Fruit type	Temp (°C)	Moisture content (%)	Density, ρ (kg m^{-3})	Thermal diffusivity, α (x 10^{-7} m^2 s^{-1})	Specific heat capacity, C_p (kJ kg^{-1} K^{-1})	Thermal conductivity, *k* (W m^{-1} K^{-1})	Reference(s)
Berries	Figs	23	40	1241	0.96		0.310	Sweat (1985)
	Avocado	41	-	-	1.54	-	-	Singh (1982)
	Avocado	28	64.7	1060	-	-	0.429	Sweat (1974)
	Tomato (pulp)	20–150	-	-	-	2.25–3.00	-	Choi & Okos (1983)
	Tomato (pulp)	22	-	1032	-	-	-	Kumar *et al*. (2008)
	Blueberry (pulp)	40	82	1001	1.51	4.050	0.64	Mercali *et al*. (2011)
	Blueberry	84.61	-	-	-	3.83	-	ASHRAE (2006)
	Blackberry	85.64	-	-	-	3.91	-	ASHRAE (2006)
	Acai (pulp)	-	93.8	1047	-	-	-	de Moura *et al*. (1998)
	Kiwi	30–90	-	-	-	3.893	-	Oliveira *et al*. (2012)
	Pomegranates	25	76.5	986.99	1.69	3.302	0.546	Mukama *et al*. (2019b)
	Cranberries	-	83.02	670	1.06	3.509	0.248	Zielinska *et al*. (2017)
	Cranberries	-	86.54	-	-	3.91	-	ASHRAE (2006)
	Raspberries	-	82.7	-	-	3.73	-	Sweat (1994)
	Berberis	50–70	19.3–74.3	-	-	1.965–3.281	0.132–0.489	Aghbashlo *et al*. (2008)
Drupes	Peach	28	88.5	930	-	-	0.581	Sweat (1974).
	Peach	14	90	980	-	3.892	0.54	Komarov (2012)
	Peach	27.4	-	-	1.39	-	-	Singh (1982)

Table 2.3 *Continued*

Category	Fruit type	Temp (°C)	Moisture content (%)	Density, ρ (kg m^{-3})	Thermal diffusivity, *α* (x 10^{-7} m^2 s^{-1})	Specific heat capacity, C_p (kJ kg^{-1} K^{-1})	Thermal conductivity, *k* (W m^{-1} K^{-1})	Reference(s)
Drupes	Peach (no stone)	25–50	85.1	-	-	3.77	-	Sweat (1994)
	Peach	-	86	-	-	-	0.58	Phomkong *et al*. (2006)
	Plums, blue	26	88.6	1130	-	-	0.551	Sweat (1974)
	Apricots	14	90	1000	-	3.134	0.5	Komarov (2012)
	Apricots	-	86.35	-	-	3.87	-	ASHRAE (2006)
	Cherry (sour)		86.13	-	-	3.85	-	ASHRAE (2006)
	Plum (no seed)	-	80.3	-	-	3.65	-	Sweat (1994)
	Plum	-	68	-	-	-	0.54	Phomkong *et al*. (2006)
	Plum	-16	-	-	-	-	0.245	Smith *et al*. (1952)
	Nectarine	8.6	82.9	990	-	-	0.585	Sweat (1974)
	Nectarine	-	-	-	-	3.5	0.65	Phomkong *et al*. (2006)
	Olive (pulp)	-	75.97	1057.6	1.239	3.609	0.473	Cuesta & Alvarez (2017)
Melons	Watermelon	-	95	1003	1.48	4.05	0.616	Ikegwu & Ekwu (2009)
	Cantaloupe Melon	-	89.78	-	-	3.93	-	ASHRAE (2006)
	Yellow melon	-	-	-	-	4.03	-	Oliviera *et al*. (2012)
Citrus	Orange (pulp)	-	82.1–82.7	1030–1060	1.5–1.56	4.025–4.068	0.63–0.66	Hidalgo (2012)
	Orange	-	-	1010	-	-	0.554	Liang *et al*. (1999)
	Orange	-	89.2	1004	1.45	3.91	0.588	Ikegwu & Ekwu (2009)

Table 2.3 *Continued*

Category	**Fruit type**	**Temp (°C)**	**Moisture content (%)**	**Density, ρ (kg m^{-3})**	**Thermal diffusivity, α (x 10^{-7} m^2 s^{-1})**	**Specific heat capacity, C_p (kJ kg^{-1} K^{-1})**	**Thermal conductivity, *k* (W m^{-1} K^{-1})**	**Reference(s)**
Citrus	Orange (peeled)	28	85.9	1030	-	-	0.580	Sweat (1974)
	Lemon	40	-	-	1.07	-	-	Singh (1982)
	Lemon	-	90	1032	1.46	3.93	0.592	Ikegwu & Ekwu (2009)
	Lemon (peeled)	28	91.8	930	-	-	0.525	Sweat (1974)
	Lime (peeled)	28	89.9	1000	-	-	0.490	Sweat (1974)
	Lime	-	90.7	1003	1.47	3.94	0.595	Ikegwu & Ekwu (2009)
	Grapefruit (peeled)	26	90.4	950	-	-	0.549	Sweat (1974)
Tropical	Pawpaw	-	88	889	1.69	3.88	0.582	Ikegwu & Ekwu, (2009)
	Mango	-	84	1068	1.39	3.78	0.562	Ikegwu & Ekwu, (2009)
	Mango (pulp)	20–80	52–90	991.2–1192	1.39	2.730–4.093	0.377–0.623	Bon *et al*. (2010)
	Mango	-10 to -30	60–80	-	3.904–6.033	1.721–2.031	0.677–1.134	Laohasongkram *et al*. (1995)
	Mango	60–100	60–80	-	1.433–2.052	3.655–3.919	0.507–0.855	Laohasongkram *et al*. (1995)
	Guava	-	81	1071	1.38	3.7	0.547	Ikegwu & Ekwu, (2009)
	Cupuacu (pulp)	25–55	89.83	1036	1.46	3.82	0.578	de Moura *et al*. (1998)
	Banana (puree)	-	-	980	-	-	0.475	Liang *et al*. (1999)
	Banana	-	74.26	-	-	3.56	-	ASHRAE (2006)
	Banana (puree)	80	-	1115	-	3.642	0.595	Cham, (1962), Ditchfield *et al*. (2007)

Table 2.3 *Continued*

Category	Fruit type	Temp (°C)	Moisture content (%)	Density, ρ (kg m^{-3})	Thermal diffusivity, α (x 10^{-7} m^{2} s^{-1})	Specific heat capacity, C_p (kJ kg^{-1} K^{-1})	Thermal conductivity, k (W m^{-1} K^{-1})	Reference(s)
Tropical	Banana	27	75.7	980	-	-	0.481	Sweat (1974)
	Banana	-	71	964	1.5	3.45	0.498	Ikegwu & Ekwu (2009)
	Banana (unripe)	-	71–21	-	1.97–1.26	1.8–3.0	0.894–0.154	Zabalaga *et al*. (2016)
	Papaya	20	-	-	-	3.02	-	Espinoza-Guevara *et al*. (2010)
	Caja (pulp)	30–90	-	-	-	4.037	-	Oliveira *et al*. (2012)
	Pineapple	27	84.9	1010	-	-	0.549	Sweat (1974)
	Pineapple	-	85	983	1.52	3.8	0.567	Ikegwu & Ekwu (2009)
	Cashew apple (pulp)	30–90	-	-	-	4.027	-	Oliveira *et al*. (2012)
	Cashew	-	88	930	1.61	3.88	0.582	Ikegwu & Ekwu (2009)
	Pitanga (pulp)	30–90	-	-	-	3.967	-	Oliveira *et al*. (2012)
	Soursop fruit (pulp)	30–90	-	-	-	3.865	-	Oliveira *et al*. (2012)
	Soursop	-	83	-	1.55	3.75	0.557	Ikegwu & Ekwu (2009)
	Graviola (pulp)	25–55	88.96	1013	1.5	3.97	0.603	de Moura *et al*. (1998)
	Cocoa (pulp)	30–90	-	-	-	3.746	-	Oliveira *et al*. (2012)
	Passion fruit (Juice)	0.4–68.8	50–80	995–1240	-	2.5–4.0	0.412–0.635	Gratao *et al*. (2005)

2.3.2. Thermal conductivity of fruit

Thermal conductivity (*k*) measures the heat conducting ability of a material. Materials with low thermal conductivity have a lower rate of heat transfer than materials with high thermal conductivity. Fruit thermal conductivity values ranged between 0.13–0.89 W m^{-1} K^{-1}, average 0.53 W m^{-1} K^{-1} (Table 2.3). Similar to specific heat capacity, fruit with high moisture content have higher values of thermal conductivity. This is attributed to the higher thermal conductivity of water compared to other fruit contents (Mohsenin, 1980; Rahman *et al*., 1997). From data that had fairly close measurement method and conditions where stated (Table 2.3), the variation between same fruit values of thermal conductivity, taking the bigger value as the denominator, was 8.81% in pear (Sweat, 1974) and (Liang *et al*., 1999). Both authors used probe method. The variation can be attributed to fruit varietal differences (microstructure) and measurement error.

Mercali *et al*. (2011), Aghbashlo *et al*. (2008), Bon *et al*. (2010) and Figura & Teixera (2007) found more dependency of thermal conductivity on moisture content than temperature. Sweat (1974) also found a strong correlation between thermal conductivity and fruit water content except for fruit considerably less dense than water. In a study to determine the thermal properties of Berberis fruit, using the transient line heat source method, Aghbashlo *et al*. (2008) also observed increase in the thermal conductivity with both moisture content and temperature increase 0.1324–0.4898 W m^{-1} K^{-1}, between 50–70 °C and 19.3–74.3% moisture content.

At low temperatures (-10 to -30) °C, Laohasongkram *et al*. (1995) observed an increase in the thermal conductivity of mangoes with a decrease in temperature. However, thermal conductivity increased with an increase in moisture content. They also observed that the thermal conductivity values of frozen mangoes were higher than values above freezing temperatures. This can be attributed to the higher thermal conductivity of ice (2.23 W m^{-1} K^{-1}) in comparison to water (0.604 W m^{-1} K^{-1}) (Spieb *et al*., 2001).

2.3.3. Thermal diffusivity of fruit

Thermal diffusivity (α) measures the rate at which heat is conducted through a material. It represents the rate of temperature change during temperature removal or addition to a given volume of food product during processing (Juliano *et al*., 2011). Thermal diffusivity relates the heat conducting ability of a material to its heat storability (Sweat, 1994). Thermal diffusivity of fruit range between 0.88–2.05 × 10^{-7} m^2 $s^{-1.}$ (Table 2.3). However, similar to specific heat and thermal conductivity, any comparison of values should be based on measurements done at similar conditions of temperature and moisture content since thermal diffusivity of fruit has been shown to be affected by temperature and moisture content (Laohasongkram *et al*., 1995; Martínez-Monzó *et al*., 2000; Bozikova 2007; Mukama *et al*., 2019b).

Temperature, moisture content and their interaction significantly affected the thermal diffusivity of mangoes at both low (-10 to -30 °C) and high temperatures (60–100 °C), rising with a rise in temperature and moisture content at high temperature measurements (Laohasongkram *et al*., 1995). However, at low temperature, a decrease in thermal diffusivity with an increase in temperature was observed for mangoes. At constant temperature, the diffusivity increased with increase in moisture content (Laohasongkram *et al*., 1995). Martínez-Monzó *et al*. (2000) and Bozikova (2007) also reported a linear increase of thermal diffusivity with increase in temperature in apples. Fruit growth stage may also affect the thermal diffusivity of fruit. For example, in Marsh grapefruit, Bennett *et al*. (1970) observed an increase in the effective thermal diffusivity as the fruit ripened, lost peel thickness and became denser.

2.4. Measurement techniques

2.4.1. Measuring the thermal conductivity of fruit

Thermal conductivity is measured in several ways depending on the type of material and the medium temperature. The two main categories of thermal conductivity measurement techniques are steady-state methods and transient methods. The steady-state technique takes measurements when the temperature of the material reaches complete equilibrium that is when the temperature at each point of the specimen is constant and does not change with time. Fig. (2.1) depicts steady-state conduction of heat through a plane wall. Eq. (2.7) gives the corresponding heat conduction equation, also called the Fourier's law, as the rate of heat flow (q) through thickness dx, in the direction normal to surface area A, under a steady state temperature difference $dT = T_1 – T_2$.

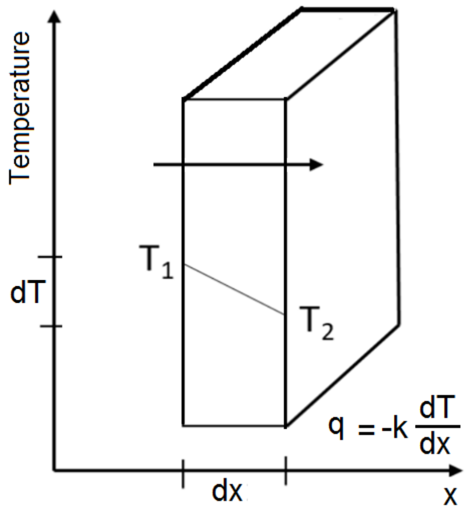

Fig. 2.1 Heat conduction through a slab material; T_1 and T_2 are surface temperatures

$$q = \frac{k(T_1 - T_2)}{dx} \tag{2.7}$$

where q is the heat flux (W m^{-2}), k is the thermal conductivity (W m^{-1} K^{-1}), dx is the thickness of the sample (m), T_1 is temperature at the high temperature (°C) side and T_2 is the temperature (°C) at the low temperature side of the sample, both kept constant in time. Steady-state technique generally takes a long time to reach the required equilibrium and may be expensive since it requires a well-designed installation system (Rozanski & Sobotka, 2013). This technique involves time independent measurements of the thermal conductivity using a heat source and heat sink principle. It is more suited for low moisture products. Notable methods in this category are the guarded hot plate, concentric cylinder and concentric sphere methods. The material to be measured is placed between the plates, one acting as a heat source while the other, a heat sink (Singh, 2006).

The transient or non-steady-state technique determine thermal conductivity using measurements taken from transient sensors during a heating process. Measurements in this category are relatively quick, which gives it an advantage over steady-state techniques (Sweat, 1994). The disadvantage is that the mathematical analysis of the data is in general more difficult. This technique has been widely used in the determination of the thermal conductivity of most foods and hence it is discussed in greater detail below. Transient methods generally employ needle probes or wires (Carslaw & Jaeger, 1959) (Fig. 2.2).

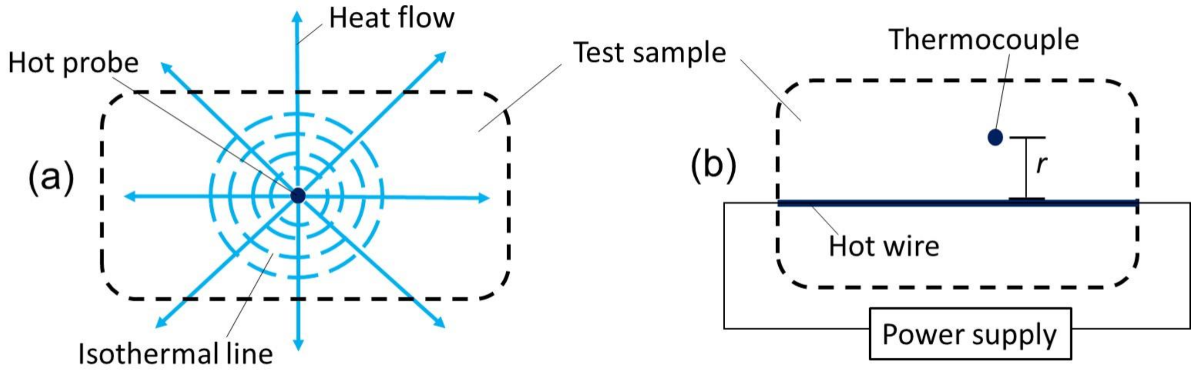

Fig. 2.2 Schematic (a) hot needle and (b) hot wire embedded in specimen

The probe method is based on the solution of the line heat source placed within an infinite, isotropic, and homogenous specimen of thermal diffusivity, α. Heat flow radially around the probe in the specimen is in accordance to the general Fourier equation. The isotherms formed within the specimen represent perfect cylinders (Fig. 2.2) of infinite length with continually increasing radii (Lockmuller *et al*., 2004). This is represented by Eq. (2.8) (Rozanski & Sobotka, 2013; Rozanski & Stefaniuk, 2016)

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \qquad (2.8)$$

where T is temperature (°C) at time t (s) and r is the radial distance from the line source (m). Single and double probes are used in the measurements. Fig. (2.3 (a)) depicts schematic view of the single-needle probe technique. In this technique, heat is applied to the needle for a duration of t_h (s) while simultaneously monitoring the temperature and then the heating is turned-off for an extra duration called the cooling-period. Then models are fitted to the temperature-time data of the heating and cooling periods to provide the thermal conductivity value. For instance, Eq. (2.9) and Eq. (2.10) are used to model the temperature-time history of the heating and cooling periods, respectively (Rozanski & Stefaniuk, 2016).

$$T = m_o + m_2 t + m_3 \ln t, \qquad 0 < t < t_h \qquad (2.9)$$

$$T = m_1 + m_2 t + m_3 \ln\left[\frac{t}{t - t_h}\right], \qquad t > t_h \qquad (2.10)$$

where m_o is the ambient temperature at time 0 (°C), m_1 is final temperature after heating (°C), m_2 is the rate of background temperature drift (°C s^{-1}), m_3 is the slope of the line relating the change in temperature against logarithm of time (°C) (Rozanski & Sobotka, 2013). Once the constants of Eq. (2.9) and Eq. (2.10) are determined through curve fitting, the thermal conductivity, k (W m^{-1} K^{-1}), is calculated as in Eq. (2.11), q (W m^{-1}) is the power dissipated per unit length of heater. Data in the linear portions of the graph of the heating and cooling phases are used for fitting the equations as the initial plot of temperature vs ln(t) and ln($t/(t-t_h)$) is nonlinear, influenced by probe thermal properties (Lockmuller *et al*., 2004; Rozanski & Sobotka, 2013).

$$k = \frac{q}{4\pi m_3} \tag{2.11}$$

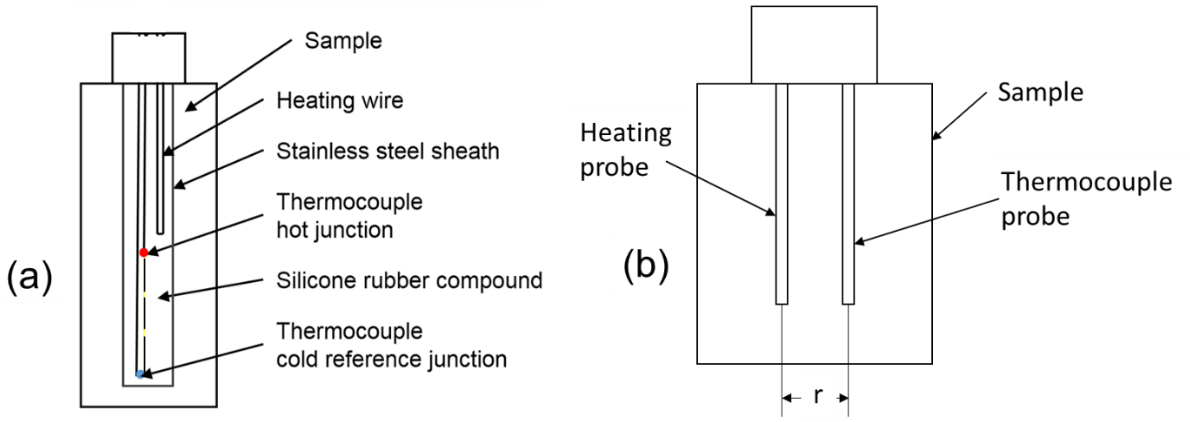

Fig. 2.3 Schematic view of the single (a) and dual (b) needle probes (Lockmuller *et al*., 2004)

The dual needle heat-pulse sensor consists two needles spaced typically 6 mm apart (Fig. 2.3 (b), r = 6 mm). One needle is a line heat source and the other is a thermocouple. A short duration pulse is applied to the heater and the thermocouple's temperature response to the heat pulse is used to determine the thermal properties of the sample. The temperature rise of the thermocouple at distance, r, is given by Eq. (2.12) (Campbell *et al*., 1991; Rozanski & Sobotka, 2013)

$$\Delta T = \frac{q}{4\pi k t} \cdot exp\left(-\frac{r^2}{4\alpha t}\right) \tag{2.12}$$

where ΔT is the temperature rise measured by the thermocouple (°C s^{-1}), r is the distance between the line heat source and the temperature sensor (m), q is the power dissipated per unit length of heater (W m^{-1}), k is the thermal conductivity (W m^{-1} K^{-1}), α is the thermal diffusivity

(m^2 s^{-1}), and t is heating time (s). Eq. (2.12) is used to fit a set of observations and with a mathematical inverse method the thermal conductivity and thermal diffusivity are calculated. After obtaining the thermal conductivity, density, ρ (kg m^{-3}) and thermal diffusivity, α (m^2 s^{-1}), the specific heat, C_p (J kg^{-1} K^{-1}) is calculated from Eq. (2.13).

$$\alpha = \frac{k}{\rho C_P} \tag{2.13}$$

Alternatively, the readings can be processed taking into consideration both the heating and cooling phases, Eq. (2.14) relates to the first t seconds, while the heat is on and Eq. (2.15) is for the cooling period, while the heat is off (Carslaw & Jaeger, 1959; Rozanski & Sobotka, 2013). Hence, the temperature-time data of the heating and cooling periods is fitted to Eq. (2.17) and Eq. (2.18) using a non-linear least squares procedure.

$$T^* = b_o t + b_1 E_i\left(\frac{b_2}{t}\right) \tag{2.14}$$

$$T^* = b_o t + b_1 \left\{E_i\left(\frac{b_2}{t}\right) - E_i\left[\frac{b_2}{t - t_h}\right]\right\} \tag{2.15}$$

$$T^* = \frac{4\pi(T - T_o)}{q} \tag{2.16}$$

where, T_o is the ambient temperature at time 0 (°C), T is the temperature (°C) after heating time (t), q is the heat input per unit length of probe (W m^{-1}). t is the instantaneous time (s) when temperature is recorded, t_h is the first seconds (s), while the heat is on, b_o, b_1 and b_2 are the constants to be fit. The thermal conductivity, k (W m^{-1} K^{-1}) and thermal diffusivity α, (m^2 s^{-1}) are then computed using Eq. (2.17) and Eq. (2.18), r is the radial distance between the two needles (m).

$$k = \frac{1}{b_1} \tag{2.17}$$

$$\alpha = \frac{r^2}{4b_2} \tag{2.18}$$

2.4.2. Measurement techniques of specific heat capacity of fruit

Different methods have been used by several researches to determine the specific heat capacity of agricultural and food materials. These include hot wire method (transient line heat source method), method of mixtures, guarded plate method, and differential scanning calorimetry (DSC) (Mohsenin, 1980; Gupta, 1990; Lozano, 2009; Zabalaga *et al*., 2016). The dual needle probe, described in section 2.4.1 above, can be used to determination the specific heat capacity, thermal conductivity, thermal diffusivity, and thermal resistivity of a material.

The method of mixtures is the most widely used technique for measuring the specific heat capacity of agricultural products due to its simplicity (Mohsenin, 1980). In this method, a sample of interest with a known mass (M_{sample}) is first set at a determined initial temperature (T_1) and then added in an adiabatic vessel (a calorimeter) at a determined initial temperature (T_2) and with known mass ($M_{calorimeter}$) and specific heat capacity ($C_{p(Calorimeter)}$). Then, the sample is mixed with a specific mass of a liquid with known properties (water, in general– M_{water}, $C_{p(water)}$) at T_2. After thermal equilibrium the entire system will attain a temperature T_3, where $T_2 < T_3 < T_1$. The sample specific heat capacity (C_p) is then obtained by applying the energy balance for the system assuming the heat loss from the sample (= $M_{sample}C_p(T_1\text{-}T_3)$) is equal to the sum of heat gain by the water (= $M_{water}\ C_{Pwater}(T_3\text{-}T_2)$) and the calorimeter (= $M_{calorimeter}\ C_{p(calorimeter)}(T_3\text{-}T_2)$) using Eq. (2.19).

$$C_P = \frac{M_{water}\ C_{P(water)}\ (T_3\ - T_2) + M_{Calorimeter}\ C_{P(calorimeter)}\ (T_3\ - T_2)}{M_{sample}\ (T_1 - T_2)} \tag{2.19}$$

In the DSC method, a single heat thermogram—a record of heat flow as a function of heat or temperature is used to calculate the specific heat of a sample. The thermogram is generated by the system recorder after the sample is placed in a special cell whose temperature is increased at a constant heating rate (Juliano *et al*., 2011). The area under the thermogram is proportional to the heat energy absorbed or lost by the product in the heating or cooling process (Mohsenin, 1980). The DSC method is based on the definition of specific heat rewritten as in Eq. (2.20) (Simon, 2000; Vozarova, 2005):

$$C_P = \frac{1}{m}\left[\frac{\partial H}{\partial T}\right] = \frac{1}{m}\left[\frac{\frac{\partial H}{\partial t}}{\frac{\partial T}{\partial t}}\right] = \frac{1}{m}\frac{\Delta P}{\beta} \tag{2.20}$$

where H is the enthalpy (J), m is the mass (kg), T the temperature (K), ΔP is difference between power (W) to the sample and the reference, and β is heating rate (K s^{-1}). The DSC method can scan a wide range of temperatures making it suitable for the determination of the effect of temperature on specific heat of foods, however, the equipment is expensive, requires calibration, and uses small sample sizes (5–15 mg) (Sweat, 1994; Laohasongkram *et al*., 1995).

Kumar *et al*. (2008) used the DSC to measure the specific heat of tomatoes at 10 °C intervals between 20 °C and 130 °C (Table 2.3).

The guarded plate method of specific heat capacity determination works on the principle that the electric heat supplied to a product in between thermal guards that are also electrically heated in a given time is equal to the heat gain by the specimen (Eq. 2.21). The specific heat is then calculated from the heat gain as in Eq. (2.22). The guards and the product are kept at the same temperature (Mohsenin, 1980). However, this method may not be fit for irregular shaped specimen like fruit unless specially shaped fitting thermal guards are available.

$$Q = C_p W \Delta T = Vit \qquad (2.21)$$

$$C_p = \frac{VIt}{W \Delta T} \qquad (2.22)$$

where C_p is the specific heat (J kg^{-1} K^{-1}), V is the average voltage in time t (V s^{-1}), I is the average current in time t (A s^{-1}) and ΔT is the temperature change (°C). Table 2.4 presents a summary of some of the common measurement methods for thermal properties and density of fruit.

Table 2.4 Summary of different methods used in the determination of thermal properties and density of fruit

Method	**Measured property**	**Operating principle**	**Limitations**	**Additional comment**	**Reference(s)**
Transient line heat source method	Specific heat capacity Thermal conductivity Thermal diffusivity	Temperature change of the wire heated by a controlled source (heat pulse) and embedded in the test material for a particular time period is dependent on the material thermal properties	Free convection due to probe heating in high moisture foods could give erroneous results Probe sizes may not be suitable for some fruit or fruit parts	Most suited for fruit Fast method High accuracy Works well at high pressure measurements	Sweat, (1974, 1994), Lozano *et al*. (1979), Laohasongkram *et al*. (1995), Denys & Hendrickx, (1999), Liang *et al*. (1999), Singh, (2006), Aghbashlo *et al*. (2008), Zhu *et al*. (2008), Alvarado *et al*. (2012)
Method of mixtures	Specific heat capacity	The specific heat is determined from the heat exchange balance after the sample is dropped in the calorimeter and equilibrium temperature is achieved. Heat loss from the measured substance = to the heat gain by water	Method assumes that heat loss that is not accounted for is negligible Needs a calibration run with reference material of known heat capacity	Modern calorimeters have an adiabatic jacket to minimise heat exchange of the calorimeter and its surroundings It's a simple and accurate method	Mohsenin, (1980), Phomkong *et al*. (2006), Aghbashlo *et al*. (2008)
Differential Scanning Calorimetry (DSC)	Specific heat capacity	Heat flow rate to the sample programmed in a specified environment is monitored vs. time or temperature. The area under the thermogram (heat flow against temperature) generated by the system recorder is proportional to the heat energy absorbed or lost by product in the heating or cooling process	Uses very small sample sizes Expensive equipment	Can scan a wide range of temperatures Suitable for the determination of the effect of temperature on specific heat of foods in short time	Mohsenin, (1980), Sweat, (1994), Laohasongkram *et al*. (1995), Moreira *et al*. (1995), Ramakumar *et al*. (2001), Kumar *et al*. (2008), Juliano *et al*., (2011), Barnwal *et al*. (2015)

Table 2.4 *Continued*

Method	Measured property	Operating principle	Limitations	Additional comment	Reference(s)
Thermal diffusivity tube	Thermal diffusivity	Based on the analytical solution for the heat diffusion equation in a long cylinder.	Suitable for fruit pulps but not whole fruit	Cylinder filled with sample, with thermocouple at thermo-centre is placed in a temperature gradient, then temperature is recorded throughout the experiment. Then temperature and time is correlated through an exponential fit	Laohasongkram *et al*. (1995), de Moura *et al*. (1988), Telis-Romero *et al*. (1998), Souza *et al*. (2008), Mercali *et al*. (2011)
Cylindrical cells method	Thermal conductivity Specific heat	Conduction inside the cell is described by the Fourier equation in cylindrical coordinates, with boundary conditions corresponding to heat transfer between two concentric cylindrical surfaces kept at constant temperature	Suited for liquid samples	The liquid whose properties are being determined fills two concentric cylinders 180 mm in length, separated by an annular space of 2 mm.	Bellet *et al*. (1975), Telis-Romero *et al*. (1998), Bon *et al*. (2010)
Pyncnometry	True density	Pyncometer, a calibrated flask that allows weighing of known volume of liquid.	Best suited for liquid samples	Measurements can be made at different temperature in a water bath	Telis & Romero (1998), Lozano (2009), Zabalaga *et al*. (2016)

Table 2.4 *Continued*

Method	Measured property	Operating principle	Limitations	Additional comment	Reference(s)
Gas stereopyncometer	True density	Balance of pressure and volume of gases in 2 chambers, one with fruit and the other without, using the ideal gas law	No significant change in moisture content should occur during the measurement Ideal for dry fruit only Small variations in gas pressure inside the sample chamber may give rise to significant errors in the measurement of volume	A pre-weighed fruit is placed in a sample holder of known volume, outgassed with helium gas, pressure is recorded. Helium is then introduced into 2nd chamber of known volume and pressure is recorded too. Method is accurate but requires very precise calibration	Karathanos & Saravacos (1993), Rodrıguez-Ramırez *et al*. (2012)
Volumetric displacement method	Apparent density	Relationship between weight and Volume of water displaced in graduated cylinder Buoyant force method is based on the Archimedes principle, the sample is weighed inside and outside of an immersion liquid of known density.	Sample should remain suspended in the liquid, not absorb liquid and not touch the bottom or the sides of the container	Easy and cheap method Applicable to samples of any shape Presence of air bubbles can cause error	Rodrıguez-Ramırez *et al*. (2012), Mukama *et al*., (2019a)

2.5. Prediction techniques

2.5.1. Frozen foods: ice fraction

In frozen foods, the fraction of ice strongly affects the thermophysical properties of the food (Frike, 2001; ASHRAE, 2006). The thermophysical properties of frozen foods vary dramatically with temperature because the ice and water fractions in the food vary with temperature and these have different thermophysical properties. Initially some water crystallises in the food, concentrating the remaining solution which further lowers its freezing point. Therefore, in predicting the thermal properties of frozen foods, it is paramount to determine how much of the water is frozen and how much remains unfrozen at a given temperature. For example, when determining the thermal conductivity of frozen foods, the thermal conductivity of the ice/water mix is determined and then combined successively with the thermal conductivities of the rest of the food constituents in the thermal conductivity models (ASHRAE, 2006; Gulati & Datta, 2013). Tchigeov (1979) proposed Eq. (2.23) for calculation of the mass fraction of ice (x_{ice}) in frozen food applicable to a wide variety of foods with satisfactory accuracy within range -45 °C ≤ T ≤ Tf, and -2 ≤ T_f ≤ -0.4 °C (Fikiin, 1996).

$$x_{ice} = \frac{1.105 x_{wo}}{\left(1 + \frac{0.7138}{ln\left(T_f - T + 1\right)}\right)} \tag{2.23}$$

where x_{wo} is the mass fraction of water in the unfrozen food, T_f is initial freezing point of food (°C), and T is food temperature (°C).

2.5.2. Predicting the thermal conductivity of fruit

Generally, food materials are non-homogeneous, varying in composition and structure not only between products, but also within a single product. Estimating the thermal properties of foods based on composition requires detailed knowledge of the mass fractions of the various food components. Constituents commonly found in fruit include water, protein, fat, carbohydrate, fibre, and ash. Standard laboratory gravimetric techniques can be used to determine the component mass fractions. Alternatively, publications such as Holland *et al*. (1991) and USDA (1975) state typical compositions for a wide range of food materials and food products. In conjunction with such composition data, the Choi and Okos (1986) model has been used to predict the thermophysical properties of the constituents as function of temperature. Then, the estimation of the thermal properties of a food product is made by taking into account the mass average of the components and the structure of the food material (i.e., how the different constituents are structured in space inside the food).

In this regard, the parallel or perpendicular models (Eq. 2.24 and Eq. 2.26) are used to estimate the thermal conductivity of food, based on analogies with electrical resistance (Murakami & Okos, 1989). The two models have been used to predict the upper and lower bounds of thermal conductivities of most foods (Fricke, 2001; ASHRAE, 2006). The parallel model is a summation of the thermal conductivities of the food constituents multiplied by their volume fractions (Eq. 2.24).

$$k = \sum x_i^v k_i \tag{2.24}$$

where x_i^v is the volume fraction of the constituent *i*, calculated using Eq. (2.25), where ρ_i is the density of the constituent *i* (kg m^{-3}):

$$x_i^v = \frac{x_i/\rho_i}{\sum(x_i/\rho_i)} \tag{2.25}$$

The perpendicular model is a reciprocal of the sum of volume fractions divided by their thermal conductivities (Eq. 2.26).

$$k = \frac{1}{\sum(x_i^v/k_i)} \tag{2.26}$$

The density of food material can be estimated based on the mass fractions of the individual components using Eq. (2.27):

$$\rho = \frac{1 - \varepsilon}{\sum(x_i/\rho_i)} \tag{2.27}$$

where ε is the food porosity, x_i is the mass fraction of the individual food constituents and ρ_i is the density of the food constituents (kg m^{-3}).

Earlier models used to predict thermal conductivity of food items include methods like dilute dispersion of small spheres in a continuous phase (Eucken, 1940) (Eq. 2.28), Levy (1981) and the Kopelman (1966) models. The models consider two distinct phases of the food materials. When foods contain more than two distinct phases, the models must be applied successively when determining thermal conductivities of such food materials (ASHRAE, 2006).

$$k = k_c \frac{1 - \left[1 - a\left({}^{k_d}/_{k_c}\right)\right] b}{1 + (a-1)b} \tag{2.28}$$

where k is the thermal conductivity of mixture (W m^{-1} K^{-1}), k_c is thermal conductivity of continuous phase (W m^{-1} K^{-1}), k_d is thermal conductivity of dispersed phase (W m^{-1} K^{-1}), a is $3k_c/(2k_c + k_d)$, b is $V_d/(V_c + V_d)$, where V_d is volume of dispersed phase (cm^3) and V_c is volume of continuous phase (cm^3).

Levy (1981) modified Eq. (2.28) to derive Eq. (2.29) for thermal conductivity determination

$$k = k_c \frac{k_2[(2+\Lambda) + 2(\Lambda - 1)F_1]}{(2+\Lambda) - (\Lambda - 1)F_1} \tag{2.29}$$

where Λ is the thermal conductivity ratio ($\Lambda = k_1/k_2$), k_1 and k_2 are thermal conductivities of food components (phases) 1 and 2, respectively. While

$$F_1 = 0.5\left\{\left(\frac{2}{\sigma} - 1 + 2R_1\right) - \left[\left(\frac{2}{\sigma} - 1 + 2R_1\right)^2 - \frac{8R_1}{\sigma}\right]^{0.5}\right\} \tag{2.30}$$

where

$$\sigma = \frac{(\Lambda - 1)^2}{(\Lambda + 1)^2 + \left({}^{\Lambda}/_{2}\right)} \tag{2.31}$$

and R_1 is the volume fraction of component 1 (Eq. 2.32)

$$R_1 = \left[1 + \left(\frac{1}{x_1} - 1\right)\left(\frac{\rho_1}{\rho_2}\right)\right]^{-1} \tag{2.32}$$

Here, x_1 is the mass fraction of component 1, ρ_1 and ρ_2 are densities (kg m^{-3}) of components 1 and 2, respectively.

Kopelman (1966) developed several expressions for thermal conductivity for homogeneous and fibrous foods: For homogeneous food materials: (a) for an isotropic, two-component system composed of continuous and discontinuous phases, in which thermal conductivity is independent of direction of heat flow and the thermal conductivity of the continuous phase is assumed to be much larger than that of the discontinuous phase (Eq. 2.33).

$$k = k_c\left[\frac{1 - L^2}{1 - L^2(1 - L)}\right] \tag{2.33}$$

(b) As in (a) but the thermal conductivity of the discontinuous phase is much higher than that of the continuous phase, Eq. (2.34) is used to determine the thermal conductivity of the mixture

$$k = k_c\left[\frac{1 - [1 - M]}{1 - M(1 - L)}\right] \tag{2.34}$$

where k_c is the thermal conductivity of the continuous phase (W m^{-1} K^{-1}) and L is the volume fraction of the discontinuous phase, $M = L^2(1–k_d / k_c)$ and k_d and k_c is the thermal conductivity of the discontinuous and continuous phases (W m^{-1} K^{-1}), respectively.

For fibrous food materials, thermal conductivity depends on the direction of heat flow relative to the food fibres (Kopelman, 1966): (a) for heat flow parallel to the food fibres (Eq. 2.35)

$$k_= = k_c\left[1 - N^2\left(1 - \frac{k_d}{k_c}\right)\right] \tag{2.35}$$

(b) For heat flow perpendicular to the food fibres (Eq. 2.36)

$$k_\perp = k_c\left[\frac{1 - P}{1 - P(1 - N)}\right] \tag{2.36}$$

where N is the volume fraction of the discontinuous phase, $P = N(1–k_d / k_c)$.

Table 2.5 lists thermal conductivity, thermal diffusivity and density models for fruit or fruit groups from experimental studies in literature. While some models are only based on the water content of the fruit, others are based on the temperature of the fruit at that particular time, while the rest consider both temperature and water content of the fruit for thermal property prediction. These models are listed in that order (water content, temperature, water content + temperature) in Table 2.5.

Table 2.5 Prediction equations for thermal conductivity (k), thermal diffusivity (α) and density (ρ) of fruit based on temperature and moisture content

Prediction equation	Type of model	Units	Fruit	Limitations	R^2	Reference
$k = 0.148 + (0.00493W)$	Linear regression	W m^{-1} °C^{-1}	Fruit & vegetables	Limited to water contents > 60% and fruit denser than water.	-	Sweat (1974)
$k = 0.283–0.256^{-0.256W}$	Least square correlation	Btu ft^{-1} h^{-1} °F^{-1}	Apple (cv. Grany S)	-	0.967	Lozano *et al*. (1979)
$k = 0.27 + 0.0037W$	Linear regression	W m^{-1} K^{-1}	Plum	-	0.98	Phomkong *et al*. (2006)
$k = -0.035 + 0.0085W$	Linear regression	W m^{-1} K^{-1}	Nectarine	-	0.95	Phomkong *et al*. (2006)
$k = 0.11 + 0.0053W$	Linear regression	W m^{-1} K^{-1}	Peach	-	0.99	Phomkong *et al*. (2006)
$k = 0.084 + 0.546\frac{W}{1+W} + 0.0059T$	Linear regression	W m^{-1} K^{-1}	Mango pulp	-	0.993	Bon *et al*. (2010)
$k = 0.003(T–273.15) + 0.2762$	Linear Regression	W m^{-1} K^{-1}	Apple (cv. Jonathan)	273–333 K	0.9989	Lisowa *et al*. (2002)
$k = 0.0031(T–273.15) + 0.2826$	Linear Regression	W m^{-1} K^{-1}	Apple (cv. Golden D)	273–333 K	0.9967	Lisowa *et al*. (2002)
$k = 0.003(T–273.15) + 0.3337$	Linear Regression	W m^{-1} K^{-1}	Apple (cv. Jonagold)	273–333 K	0.9902	Lisowa *et al*. (2002)
$k = (0.232 \pm 0.003) + (0.359 \pm 0.004)W + ((1.12 \pm 0.02) \times 10^{-3})T$	Linear polynomial	W m^{-1} °C^{-1}	Passion fruit juice	-	0.996	Gratao *et al*. (2005)
$k = 0.459–7.2 \times 10^{-3}T–2.5 \times 10^{-3}W + 1.7 \times 10^{-4}TW$	Linear regression	W m^{-1} K^{-1}	Mango	60–100 °C	0.823	Laohansongkram *et al*. (1995)

Table 2.5 *Continued*

Prediction equation	Type of model	Units	Fruit	Limitations	R^2	Reference
$k = 0.099–9.0 \times 10^{-3}T + 0.010W + 4.9 \times 10^{-4}T^2$	Linear regression	W m^{-1} K^{-1}	Mango	-10 to -30 °C	0.908	Laohansongkram *et al.* (1995)
$k = 0.0797 + 0.5238W + 0.00058T$	Linear regression	W m^{-1} °C^{-1}	Orange juice	-	0.97	Telis-Romero *et al.* (1998)
$\alpha = 0.1273 + 0.0003T + 4E\text{-}06T^2$	2nd order polynomial correlation	10^6 m^2 s^{-1}	Tomato puree	20–130 °C	0.995	Kumar *et al.* (2008)
$a = 0.0068(T–273.15) + 0.9968$	Linear Regression	10^7 m^2 s^{-1}	Apple (cv. Idared)	273–333 K	0.9979	Lisowa *et al.* (2002)
$a = 0.0047(T–273.15) + 1.0292$	Linear Regression	10^7 m^2 s^{-1}	Apple (cv. Jonathan)	273–333 K	0.9907	Lisowa *et al.* (2002)
$a = 0.0057(T–273.15) + 1.0005$	Linear Regression	10^7 m^2 s^{-1}	Apple (cv. Golden D)	273–333 K	0.9952	Lisowa *et al.* (2002)
$a = 0.0053(T–273.15) + 1.1127$	Linear Regression	10^7 m^2 s^{-1}	Apple (cv. Jonagold)	273–333 K	0.9819	Lisowa *et al.* (2002)
$\alpha \times 10^7 = 3.921–0.058T–0.024W + 4.7 \times 10^{-4}TW + 2.1 \times 10^{-4}T^2$	Linear regression	m^2 s^{-1}	Mango	60–100 °C	0.943	Laohansongkram *et al.* (1995)
$\alpha \times 10^7 = 0.026–0.232T + 0.041W–1.3 \times 10^{-4}TW–5.3 \times 10^{-3}T^2$	Linear regression	m^2 s^{-1}	Mango	-10 to -30 °C	0.932	Laohansongkram *et al.* (1995)
$\alpha_{exp} = 7.9683 \times 10^{-8} + 5.9839 \times 10^{-8}W + 0.0215 \times 10^{-8}T$	Linear regression	10^{-7} m^2 s^{-1}	Orange juice	-	0.97	Telis-Romero *et al.* (1998)
$\rho = \dfrac{\rho_W}{(0.599 \pm 0.004) + (0.421 \pm 0.006)W}$	Linear polynomial	kg m^{-3}	Passion fruit juice	-	0.991	Gratao *et al.* (2005)

Table 2.5 *Continued*

Prediction equation	Type of model	Units	Fruit	Limitations	R^2	Reference
$\rho = 0.636 + 0.102\ InW$	Least square correlation	g cm^{-3}	Apple (cv. Grany S)	-	0.978	Lozano *et al*. (1979)
$\rho = 1206 + 110\left(\frac{M_W}{M_{WO}}\right) - 260\left(\frac{M_W}{M_{WO}}\right)^2$	Empirical model	kg m^{-3}	Plum	-	0.87	Phomkong *et al*. (2006)
$\rho = 677 + 812\left(\frac{M_W}{M_{WO}}\right) - 477\left(\frac{M_W}{M_{WO}}\right)^2$	Empirical model	kg m^{-3}	Peach	-	0.87	Phomkong *et al*. (2006)
$\rho = 867 + 585\left(\frac{M_W}{M_{WO}}\right) - 411\left(\frac{M_W}{M_{WO}}\right)^2$	Empirical model	kg m^{-3}	Nectarine	-	0.87	Phomkong *et al*. (2006)
$\rho = 1428.5 – 454.9W – 0.231T$	Linear regression	kg m^{-3}	Orange juice	-	0.97	Telis-Romero *et al*. (1998)
$\rho = (686 \pm 21) + (1008 \pm 10)^{((-1.2 + 0.1)W)} – (0.55 \pm 0.01)T$	Linear polynomial	kg m^{-3}	Passion fruit juice	-	0.999	Gratao *et al*. (2005)
$\rho = 1417 - 453.2\frac{W}{1+W} + 0.1878T$	Linear regression	kg m^{-3}	Mango pulp	-	0.995	Bon *et al*. (2010)

T = temperature (°C, except for Lisowa *et al*. (2002) in K), *W* = Water content (w/w (wet basis) except for Bon *et al*. (2010) and Lozano *et al*. (1979) on dry basis, Laohasongkram *et al*. (1995) and Sweat *et al*. (1974) on %), M_W/M_{WO} = moisture content ratio from initial (M_{WO}) to moisture content at measurement time (M_W).

2.5.3. Predicting the specific heat capacity of fruit

The specific heat capacity of a food item at temperatures above its initial freezing point can be obtained based on generalized predictive models for specific heat capacity of foods based on composition as given by the Choi and Okos (1986) model (Eq. 2.37).

$$C_P = \sum c_{Pi}\, x_i \tag{2.37}$$

where C_{pi} is the specific heat capacity of the individual food components (kJ kg^{-1} K^{-1}) and xi is the mass fraction of the food components. In the absence of detailed composition of a food, Chen (1985) proposed a simpler model (Eq. 2.38) based on the mass fractions of solids (x_s) in the unfrozen food item.

$$C_P = 4190 - 2300x_s - 628x_s^3 \tag{2.38}$$

Below freezing point, Eq. (2.39) (Schwartzberg, 1981) and Eq. (2.40) (Chen, 1985) can be used to predict the apparent specific heat of the frozen material. Apparent specific heat considers the sensible heat from temperature change and latent heat from fusion of water to make ice (Fricke, 2001; ASHRAE, 2006).

$$C_a = \mathrm{C}_f + (x_{wo} - x_b)\left[\frac{L_O\left(t_o - t_f\right)}{t_o - t}\right] \tag{2.39}$$

$$C_a = 1.55 + 1.26x_s - \frac{x_s R T_O^2}{M_s t^2} \tag{2.40}$$

where C_a is the apparent specific heat (kJ kg^{-1} K^{-1}), C_f is specific heat of fully frozen food (kJ kg^{-1} K^{-1}), x_{wo} is mass fraction of water above initial freezing point, x_b is mass fraction of bound water, L_o is latent heat of fusion of water (kJ kg^{-1}), t_o is freezing point of water (°C), t_f is initial freezing point of food (°C), t is food temperature (°C), x_s is mass fraction of solids, R is universal gas constant, T_o is freezing point of water (°C) and M_s is relative molecular mass of soluble solids in food.

Simple linear models such as Siebel model (1982) have also been used to predict specific heat capacity of foods. These equations are obtained from curve fitting of experimental data. Table 2.6 lists some examples of models in this category. Similar to thermal conductivity models, while some of the models consider water content of the fruit temperature only, other models are based on the temperature of the fruit, while the rest are based on both water content and the fruit temperature.

Table 2.6 Prediction equations for specific heat capacity of fruit

Prediction equation	Units	Fruit	Temp range (K)	R^2	Reference
$C_p = 0.837 + 3.349W$	kJ kg^{-1} K^{-1}	All foods	-	-	Siebel (1982)
$C_p = 1.382 + 2.805W$	kJ kg^{-1} K^{-1}	All foods	$T \geq T_{cr}$	-	Fikiin & Fikiin (19990
$C_p = 2.11 + 0.0017\ W$	kJ kg^{-1} K^{-1}	Plum	-	0.99	Phomkong *et al.* (2006)
$C_p = 2.89 + 0.012\ W$	kJ kg^{-1} K^{-1}	Nectarine	-	0.90	Phomkong *et al.* (2006)
$C_p = 2.53 + 0.017\ W$	kJ kg^{-1} K^{-1}	Peach	-	0.99	Phomkong *et al.* (2006)
$C_p = 10.581\ (T–273.15) + 2891.3$	kJ m^{-3} K^{-1}	Apple (cv. Golden D)	273–333	0.9939	Lisowa *et al.* (2002)
$C_p = 9.0199\ (T–273.15) + 3060.9$	kJ m^{-3} K^{-1}	Apple (cv. Jonagold)	273–333	0.9917	Lisowa *et al.* (2002)
$C_p = 3913.5 + 1.016\ T - 0.0017\ T^2$	J kg^{-1} K^{-1}	Tomatoes	293–403	0.938	Kumar *et al.* (2008)
$C_p = 1.00802 + 0.01897\ W + 0.001188\ T$	kJ kg^{-1} K^{-1}	Berberis	-	0.9939	Aghbashlo *et al.* (2008)
$C_p = 1.119 + 3.274 \frac{W}{1+W} + 0.00152\ T$	kJ kg^{-1} K^{-1}	Mango pulp	-	0.995	Bon *et al*. (2010)
$C_p = 1424.34 + 2673.19\ X_W + 2.446\ T$	J kg^{-1} K^{-1}	Orange juice	-	0.97	Telis-Romero *et al.* (1988)

T = temperature (°C, except for Lisowa *et al*. (2002) in K), W = Water content (w/w (wet basis) except for Bon *et al*. (2010) on dry basis, and Aghbashlo *et al*. (1974) on %).

2.6. Respiration and transpiration behaviours of fruit

2.6.1. Respiration of fruit

The respiration and transpiration activities of produce are crucial considerations in designing and operating thermal processes. Respiration is an enzymatic process by which fruit cells convert sugars and oxygen into carbon dioxide, water, and heat—heat of respiration (Eq. 2.41). This heat of respiration contributes to the total cooling load in cold chain operations (Mishra & Gamage, 2007). Exhaustion of the sugar reserves from the fruit leads to senescence (ageing) and then death or decay of the fruit. Proper ventilation of packaged produce and gas control in modified and controlled atmosphere packaging prevent these unwanted changes (Tano *et al*., 2007; Torrieri *et al*., 2009; Caleb *et al*., 2012; Belay *et al*., 2016, 2017).

$$C_6H_6O_2 + \ 6O_2 \rightarrow 6CO_2 + 6H_2O + 2816\ kJ \qquad (2.41)$$

Fruit are classified as either climacteric or non-climacteric based on their respiratory patterns. Climacteric fruit can be harvested at maturity stage but before ripening, at this stage respiration is minimum. They experience a respiratory climacteric characterised by a rapid rise in respiratory rate at start of ripening that slows down when the fruit is fully ripe (Mishra & Gamage, 2007). During ripening, climacteric fruit produce a lot of ethylene, thus ethylene treatment is used to control the rate and uniformity of ripening of climacteric fruit (Kader & Barret, 2003). Examples include apple, pear, bananas, peach, plums, tomatoes etc. Non-climacteric fruit ripen only when still attached to the parent plant. Their sugar acid content does not increase once detached from the plant. Their respiration rates progressively slow down as they grow and after harvest. Non-climacteric fruit produce very little ethylene and do not respond to ethylene ripening treatment (Phan *et al*., 1975). Examples include berries, citrus, pomegranate, pineapple, etc.

Respiration rate can be calculated from carbon dioxide evolution and oxygen consumption as in Eq. (2.42) and Eq. (2.43), respectively (Caleb *et al*., 2012). The percentages of these gases are measured by taking head space gas concentration of fruit samples in closed jar (closed system method of determining fruit respiration).

$$R_{CO_2} = \frac{V_f}{W}\frac{(y_{CO_2} - {y^i}_{CO_2})}{(t - t_i)\ x\ 100} \qquad (2.42)$$

$$R_{O_2} = \frac{V_f}{W}\frac{({y^i}_{O_2} - y_{O_2})}{(t - t_i)\ x\ 100} \qquad (2.43)$$

where R_{CO2} and R_{O2} is the carbon dioxide production rate and oxygen consumption rate (ml kg^{-1} h^{-1}), respectively, V_f is the free volume in the jar minus volume occupied by fruit (ml), W is weight of fruit (kg), y_{CO2} and y^i_{CO2} are concentration of carbon dioxide (%) at time t (h) and initial time–time zero, t_i (h), respectively, and y_{O2} and y^i_{O2} are concentration of oxygen (%) at time t (h) and initial time–time zero, t_i (h), respectively.

The respiratory heat is then determined from Eq. (2.44) (Kang & Lee, 1998; Song *et al*., 2002)

$$Q_r = \left(\frac{2816}{6}\right) x \left(\frac{R_{CO_2} + R_{O_2}}{2}\right) \xi \qquad (2.44)$$

where Q_r is the heat of respiration (J kg^{-1} h^{-1}), ξ is the amount of heat produced out of the total respiration energy. ξ varies between 0.8–1.0 (Song *et al.*, 2002). Table 2.7 gives a list of the respiration heat of selected fruit from literature at 20 °C.

Table 2.7 Heat of respiration of fruit at 20 °C

Fruit	**Heat of respiration (mW kg^{-1})**	**Reference**
Avocado	218.7–1029.1	Lutz & Hardenburg (1968)
Strawberries	303.1–581.0	Lutz & Hardenburg (1968); Maxie *et al.*, 1959
Blueberries	153.7–259.0	Lutz & Hardenburg (1968)
Pears	89.2–207.6	Lutz & Hardenburg (1968)
Apples	50.0–103.8	Lutz & Hardenburg (1968)
Grapes	97.0	Lutz & Hardenburg (1968); Lutz (1938)
Plums	53.3–77.1	Claypool & Allen (1951)
Watermelon	51.4–74.2	Lutz & Hardenburg (1968); Scholz *et al.* (1963)

2.6.2. Fruit transpiration

Transpiration (moisture loss) in fruit involves the transport of moisture through the skin of the commodity, evaporation of this moisture from the commodity surface and the convective mass transport of the moisture to the surrounding. Excessive moisture loss leading to shrivel is a main challenge in fresh fruit markets affecting saleable weight, appearance, texture, nutritional quality and fruit flavour (Kang & Lee, 1998; Mukama *et al.*, 2019a).

The rate at which fruit under storage lose moisture is dependent on the prevailing vapour pressure deficit in the surrounding atmosphere, rate of air movement around the produce, fruit surface area to volume ratio, skin structure, heat of respiration, maturity level, and number of pores on fruit surface (Mishra & Gavane, 2007). Eq. (2.45) gives a simple model for moisture transport (Sastry *et al.*, 1978; Mishra & Gavane, 2007).

$$M = k_t\,(P_S - P_a) \qquad (2.45)$$

where M is the transpiration rate (mg kg^{-1} s^{-1}), k_t the transpiration coefficient of particular fruit (mg kg^{-1} s^{-1} Pa^{-1}), P_a ambient vapour pressure (Pa), and P_s evaporative vapour pressure (Pa). The transpiration coefficient represents the reciprocals of resistance of moisture transfer, this resistance depends on the surface structure of the fruit, fruit respiration, and dissolved substances in the fruit water (Sastry *et al*., 1978; Becker & Fricke, 1996).

Energy to drive moisture from the fruit surface is both internal (heat of respiration) and external (convective heat from fruit surrounding), this is shown in Eq. (2.46) (Kang & Lee, 1998). The internal and external heat energies are used for latent heat of moisture evaporation and sensible heat of fruit temperature change (Kang & Lee, 1998). This heat balance is shown in Eq. (2.47) (Song *et al*., 2002).

$$L_m = \frac{Q_r W + hA(T_a - T_p)}{\lambda} \tag{2.46}$$

$$Q_r W + hA(T_a - T_p) = L_m \lambda + W C_p \frac{\partial T_p}{\partial t} \tag{2.47}$$

where L_m is the rate of moisture evaporation from produce (kg h^{-1}), Q_r is the respiratory heat (J kg^{-1} h^{-1}), W is the weight of fruit (kg), h is the convective heat transfer coefficient of the fruit (J m^{-2} °C^{-1} h^{-1}), A is the surface area of fruit (m^2), T_a is ambient temperature (°C), T_p fruit temperature (°C), λ is the latent heat of moisture evaporation (J kg^{-1}), C_p is specific heat of fruit (J kg^{-1} °C^{-1}), and t is time (h). Predicting moisture loss of produce and associated heat production/loss is crucial for the proper design of postharvest handling processes, packaging and predicting the fresh life of fresh produce (Kang & Lee, 1998; Song *et al*., 2002).

2.7. Conclusions and future prospects

Fruit postharvest handling and processing to improve their useful life and minimise wastage is a necessity to feed the ever-increasing global population. To achieve this, the science of these foods including their thermophysical properties are necessary to design optimal handling and processing practices. In this paper, the thermophysical properties of different fruit was reviewed, some preferred and most appropriate measurement methods described, comparison between property data from different authors made and some thermophysical properties prediction equations have been discussed. The thermophysical properties have been found to depend on temperature, moisture content, pressure, and vary between fruit. Given the high properties variability, accurate properties data of each product is necessary to effect the best handling and processing practices at a given condition of pressure, temperature, and product moisture content. Future research should focus on filling the gap of missing thermophysical properties data of particular fruit at different conditions of temperature and pressure, developing easy and fast tools and devices compatible with most fruit to enable quick and accurate measurement and traceability of property data in order to enable effective, efficient, and quick processing and preservation decisions.

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Declaration by the candidate

With regard to Chapter 3, pages 64–85, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
Compiled and edited manuscript in its entirety throughout the publication process	80

The following co-authors have contributed to Chapter 3, pages 64–85:

Name	e-mail address	Nature of contribution	Extent of contribution (%)
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Declaration with signature in possession of candidate and supervisor **Signature of candidate**	16/08/2019 **Date**

Declaration by co-authors

The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 3, pages 64–85,
2. no other authors contributed to Chapter 3, pages 64–85 besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3, pages 64–85 of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019
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Chapter 3

Thermal properties of whole and tissue parts of pomegranate (*Punica granatum*) fruit

Abstract

The thermal properties of pomegranate whole fruit (cvs 'Wonderful' and 'Acco') and fruit parts (epicarp, mesocarp, and arils) were experimentally determined. A transient heating probe system was first calibrated and used for accurate measurement of the specific heat capacity, thermal conductivity, and thermal diffusivity over a temperature range of 7–45 °C. The thermophysical properties did not vary significantly between the two cultivars. The density of the whole 'Wonderful' and 'Acco' fruit was 986.99 ± 23.82 kg m^{-3} and 1041.23 ± 18.93 kg m^{-3}, respectively. The epicarp of both cultivars had significantly lower density compared to the mesocarp and arils. The values of thermal conductivity and diffusivity of the two pomegranate cultivars increased significantly with an increase in tissue temperature. In both cultivars, the aril part was observed to have the highest values of thermal conductivity and specific heat capacity. For 'Acco' at 7 °C, values were 0.419 ± 0.047 W m^{-1} K^{-1} and 2775.244 ± 298.120 J kg^{-1} K^{-1}, respectively, compared to the mesocarp (0.352 ± 0.040 W m^{-1} K^{-1} and 2560.803 ± 231.028 J kg^{-1} K^{-1}) and epicarp (0.389 ± 0.030 W m^{-1} K^{-1} and 2681.888 ± 135.460 J kg^{-1} K^{-1}). For both 'Wonderful' and 'Acco', the in-plane thermal property values (measured along layers of peel slices) were the same as the cross-plane property values (measured through layers of slices).

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3.1. Introduction

Pomegranate fruit markets are witnessing continuous growth due to increasing consumer awareness regarding health benefits associated with the fruit (Rahmani *et al*., 2017). The cultivation of pomegranate trees, native to the area between Iran and northern India is now widespread all over the world: in Mediterranean basin, India, the drier parts of Southeast Asia, Malaya, and tropical Africa. The total world production is currently estimated at 3 million tons per year (Erkan & Dogan, 2018). Europe is a net importer of fresh pomegranates, their total import volume increased from 64,000 tons in 2012 to 102,000 tons in 2016 (CBI, 2018). Most of these imports are from developing countries, such as Colombia, Peru, and South Africa. South African pomegranate exports are estimated to grow to over 1.9 million 4.3 kg equivalent cartons by 2020 (POMASA, 2018).

Following this, studies to maintain quality during harvesting, packaging, transport and storage of pomegranates are increasing (Opara *et al*., 2009; Fawole & Opara, 2013; Arendse *et al*., 2014; Ambaw *et al*., 2017). The limiting factors to prolonged storage of pomegranates are weight loss and shrinkage (Mukama *et al*., 2019), decay, blemishes appearance on skin (especially scalds), impaired sensory attributes, and taste (Elyatem & Kader, 1984; Ben-Arie & Or, 1986; Koksal, 1989). Adequate implementation, monitoring, and management of the cold chain is essential to maintain postharvest quality of pomegranate fruit. The recommended temperature and relative humidity (RH) conditions for pomegranate handling can vary from (5 to 8) °C and 90% to 95% RH, respectively, depending on cultivar, postharvest treatment, and production area (Kader, 2006; Arendse *et al*., 2014; Mukama *et al*., 2019). Cold chain handling of pomegranate fruit is also affected by the type of packages used in handling the fruit (Ambaw *et al*. 2017; Mukama *et al*., 2017). Proper design and execution of these processes require thermal data.

Thermal properties characterize the rate and degree of heat exchange between produce and its surrounding. The data is vital for the design and implementation of handling, processing, and preservation processes (Singh, 2006; Carson *et al*., 2016). The most important thermal properties that influence process and system design are the specific heat, thermal conductivity, and thermal diffusivity (Mohsenin, 1980; Sweat, 1994). Fruit thermal properties vary between fruit type, between cultivars, and in the same fruit between tissue parts (Lisowa *et al*., 2002; Ikegwu & Ekwu, 2009; Espinoza-Guevara *et al*., 2009; Cuesta & Alvarez, 2017).

Several studies have investigated the thermal properties of different horticultural crops experimentally or by use of mathematical models (Sweat, 1974; Lisowa *et al*., 2002; Lozano, 2009; Cuesta & Alvarez, 2017). Fruit being biological materials undergo complex enzymatic and physiological changes in their postharvest life (Aremu & Fadele, 2010; Modi *et al*., 2013). These alter their composition and properties in time. Processes like moisture loss from fruit or physiological breakdown of fruit sugars during respiration into CO_2, water, and heat have the potential to change the thermal properties of these products at different handling conditions over time (Farinu & Baik, 2007; Mamani, 2015).

Many studies assumed fruit as a homogeneous solid system with effective thermal properties (Lozazo *et al*., 1979; Farinu & Baiik, 2007; Ikegwu & Ekwu, 2009; Zabalaga *et al*., 2016). However, knowledge of thermal properties of the different parts of a fruit (Mukama *et al*., 2018) are crucial for the detailed investigation of the spatiotemporal temperature distribution inside the fruit. This is especially crucial for fruit containing prominent stony core surrounded by fleshy or pulp tissue, such as mangoes, cherries, plums, and so forth. The ligneous core—the seed—has radically different physical properties different from the edible part, the pulp, and this may affect the thermal properties. For such fruit, it is important to know the cooling history of the flesh part, the stone part, and the stone-flesh interface to accurately model the cooling and heating process. Since the seed part is prominent, it plays a significant role in the moisture and heat transfer process (Cuesta & Alvarez, 2017).

Similarly, the anatomy of pomegranate fruit is complex, with a leathery rind (or husk or peel) enclosing many seeds surrounded by the juicy arils, which comprise the edible portion of the fruit. The various parts of the fruit may thus have significantly different property values that approximating the fruit as a homogeneous solid is unrealistic. Literature on thermal data of pomegranate fruit or its parts is lacking. Hence, the main objective of this study was to obtain the thermal properties of the whole and tissue parts of pomegranate fruit. This work focused on experimental measurement of the thermal properties of two different commercially important pomegranate fruit cultivars ('Wonderful' and 'Acco') at different temperatures.

3.2. Materials and methods

3.2.1. Fruit

Two cultivars of fresh pomegranate fruit (cvs. Wonderful and Acco) were procured at commercial maturity during the 2017 season from Sonlia Pack-house (33°34′851″S, 19°00′360″E), Western Cape, South Africa. 'Acco' (sweet cultivar, early season) was harvested in January/February while ‘Wonderful’ (sweet/sour cultivar, late season) was harvested in March/April. Fruit were transported to Stellenbosch University Postharvest Technology Research Lab and stored at 5 °C and 90% RH before measurements.

3.2.2. Sample preparation

3.2.2.1. Whole fruit

A sample of ten fruit of each pomegranate cultivar was randomly selected for each of the tests. The mean fruit weight was 509.9 ± 21.8 g and 274.2 ± 19.09 g for ‘Wonderful’ and ‘Acco’, respectively. Blemish-free fruit were used.

3.2.2.2. Fruit parts

Fig. 3.1 (a) depicts the structure of a typical pomegranate fruit. To measure the thermal properties of the different fruit parts, fruit were hand peeled (Fig. 3.1 (b)) and carefully separated into the epicarp (peel; Fig. 3.1 (c)), mesocarp (albedo; Fig. 3.1 (d), and arils (Fig. 3.1 (e)). In addition, the arils of the two cultivars were juiced to measure the thermal properties of the juices.

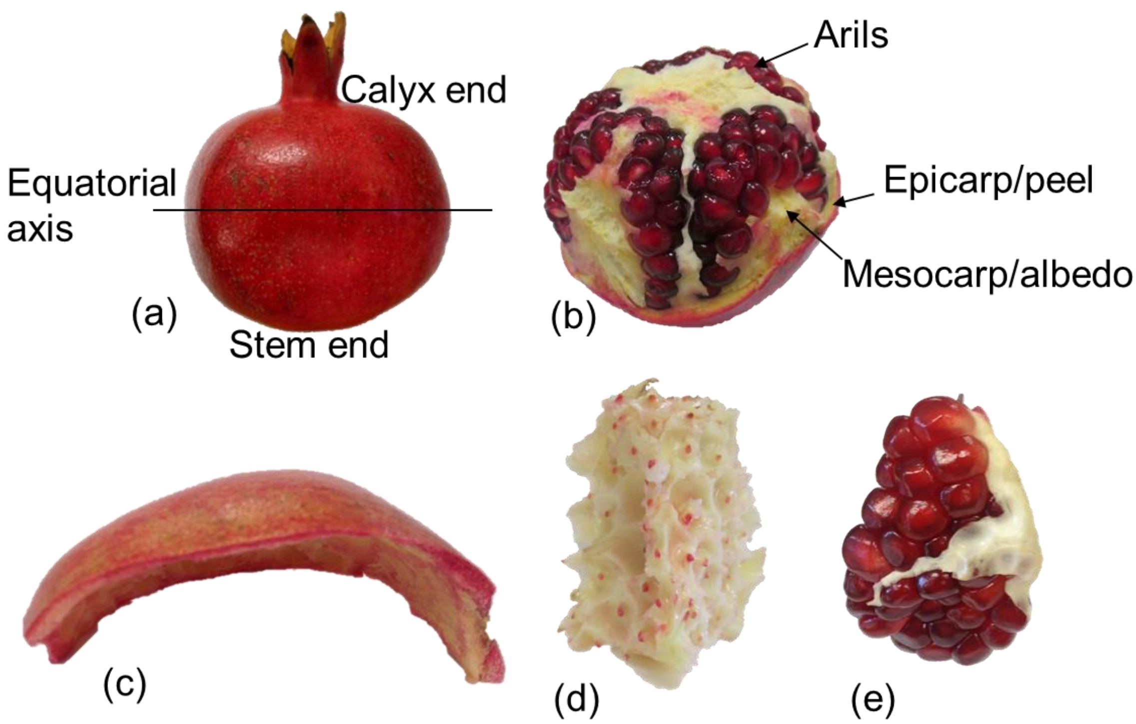

Fig. 3.1 Structure of a typical pomegranate fruit (a) the axis labels of the whole fruit, (b) the internal parts of the fruit after hand peeled, (c) the epicarp (peel), (d) the mesocarp (albedo) and (e) the arils

3.2.3. Measurement of thermal properties

3.2.3.1. Moisture content

Whole fruit moisture content was determined by drying dismantled fruit (arils separated from mesocarp; mesocarp and epicarp cut into small pieces onto an aluminium foil) at 105 °C in an oven until a constant weight reading is reached (Umeta *et al*., 1995; Al-Said *et al*., 2009). Dry samples were cooled in a desiccator before weight measurements. Measurements were done in 10 replications.

The moisture content of the fruit parts (epicarp, mesocarp, and arils) was measured using a digital moisture meter (Kern & Sohn GmbH, Model DBS60-3, Balingen, Germany). For each of the fruit part samples, 5 g of tissue was placed in a dish acclimatized to room temperature, the instrument heated cover was then closed, and meter turned on. The meter uses a 400 W halogen quartz glass heater to dry the sample while simultaneously measuring the weight change and calculates the moisture content by gravimetric analysis (Li & Kobayashi, 2005). The measuring process ends automatically when the set minimum weight change (ΔM (0.02%)) remained constant for 30 seconds. Final moisture content of samples displayed was recorded when drying was complete. Drying was done at 105 °C in standard drying mode. The mean and the standard deviation of the values were determined from ten replications.

3.2.3.2. Density determination

The weight of each sample fruit and individual fruit parts of the two cultivars was determined using a digital weighing scale (Mettler Toledo, Model ML 3002E, Switzerland, with 0.0001 g accuracy). Correspondingly, the volume of each fruit and individual fruit parts was measured using the water displacement method to determine the density (Owolarafe *et al*., 2007; Rodríguez-Ramírez et al. 2012).

3.2.3.3. Thermal conductivity, thermal diffusivity, and specific heat measurement

Thermal conductivity, diffusivity, and volumetric specific heat of the whole fruit and the fruit parts (epicarp, mesocarp, and arils) were determined using the single needle (Fig. 3.2 (a)) and dual needle (Fig. 3.2 (b)) KD2 Pro multimeter (Decagon Devices, Inc., USA). The KD2 Pro multimeter uses the transient line heat source method and inbuilt algorithms to give direct readings of the thermal properties following temperature measurements made during a heating and a cooling interval.

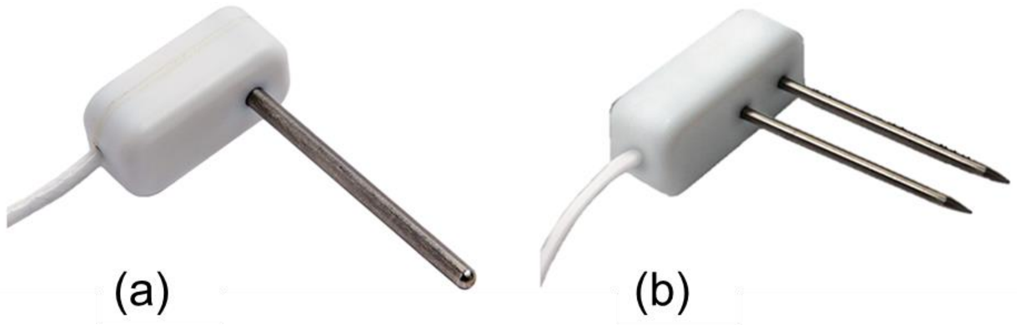

Fig. 3.2 Thermal property meter sensors. Single needle (a) and dual needle (b), KD2 Pro multimeter (Decagon Devices, Inc.)

In the dual needle sensor, heat is applied to one of the needles (heating needle) for a set time t_h (s) while the temperature (T, °C) of the second needle (temperature monitoring needle) is recorded. The two needles are 0.006 m apart. The readings are then processed as in Eq. (3.1), where T_o (°C) is the ambient temperature at time 0, q (W m^{-1}) is the heat input per unit length of probe. The calculated data—T^* is fit to Eq. (3.2) (for the first t_h seconds, while the heat is on) and Eq. (3.3) (during the cooling period, while the heat is off) using a non-linear least squares procedure (Decagon devices, Inc.; Rozanski & Stefaniuk, 2016).

$$T^* = \frac{4\pi(T - T_o)}{q} \tag{3.1}$$

$$T^* = b_o t + b_1 E_i\left(\frac{b_2}{t}\right) \tag{3.2}$$

$$T^* = b_o t + b_1\left\{E_i\left(\frac{b_2}{t}\right) - E_i\left[\frac{b_2}{t - t_h}\right]\right\} \tag{3.3}$$

where t (s) is the instantaneous time when temperature is recorded, t_h (s) is the first seconds, while the heat is on, E_i is exponential integral, b_o, b_1 and b_2 are the constants to be fit. The thermal conductivity (k, W m^{-1} K^{-1}) and thermal diffusivity (α, m^2 s^{-1}) are then computed using Eq. (3.4) and Eq. (3.5), r = radial distance between the two needles of the double needle sensor (m).

$$k = \frac{1}{b_1} \tag{3.4}$$

$$\alpha = \frac{r^2}{4b_2} \tag{3.5}$$

For the single needle algorithm, heat is applied to the needle for a time t_h (s). Temperature is monitored during heating and for an additional time equal to t_h after heating—cooling cycle. The temperatures during heating and cooling are computed using Eq. (3.6) and Eq. (3.7), respectively (Decagon devices, Inc.; Rozanski & Sobotka, 2013; Rozanski & Stefaniuk, 2016):

$$T = m_o + m_2 t + m_3 \ln t \tag{3.6}$$

$$T = m_1 + m_2 t + m_3 \ln\left[\frac{t}{t - t_h}\right] \tag{3.7}$$

$$k = \frac{q}{4\pi m_3} \tag{3.8}$$

where m_o (°C) is the ambient temperature at time 0, m_1 (°C) is final temperature after heating, $m_2 t$ (°C) is the rate of background temperature drift, m_3 is the slope of the line relating temperature rise to logarithm of temperature, k is the thermal conductivity (W m^{-1} K^{-1}), and q is the heat per unit length of probe (W m^{-1}). The thermal conductivity (k, W m^{-1} K^{-1}) is then calculated as in Eq. (3.8). While the dual needle sensor gives readings of the thermal conductivity, thermal diffusivity, thermal resistivity, and volumetric specific heat, the single needle sensor gives readings of the thermal conductivity and resistivity only. This is because determination of thermal diffusivity and heat capacity require a measurement some distance from the heat source (Decagon devices, Inc.; Mohsenin, 1980).

For the whole fruit, the SH-1 needle was inserted fully into four positions on the fruit surface, two on opposite sides along the equatorial axis of the fruit, one on the stem end and the other on the calyx end of the fruit (Fig. 3.1 & 3.3 (a)). The probe was allowed 10 minutes to equilibrate before it was switched on. Thermal conductivity, thermal diffusivity, and volumetric specific heat were recorded. Average property readings of one fruit were then calculated from the four records. Measurements were made on 10 replications of each cultivar at 7 °C in the cold room, 25, 35, and 45 °C in the hot air oven. Similarly, the SH-1 needle was also inserted into the albedo and the arils as shown in Fig. 3.3 (b and c), allowed 10 minutes to equilibrate before being switched on, records of thermal conductivity, volumetric specific heat, and thermal diffusivity were taken at 7 °C in the cold room. All samples were 0.015 m parallel to the sensor in all directions, the smallest value allowed to minimize error due to heat pulse

(Decagon devices, Inc.), and long enough to cover the length of the probe. Measurements were done in 10 replications. The process was repeated for temperatures 25, 35, and 45 °C in the hot air oven.

Thermal conductivity of the juice was determined using the KS-1 needle (Fig. 3.3(d)) as it applies a very small amount of heat and short heating time preventing free convection in liquid samples (Decagon devices, Inc.). Readings were also taken for the temperatures and test conditions as described above for the other pomegranate fruit parts.

3.2.4. Measuring the thermal properties of the epicarp

The full length of the sensor needle must be completely covered by the sample material for the measurement (Decagon Devices Inc.). This was not possible for the epicarp due to its small thickness (≈ 4 mm). To use the sensor needle, ten circular slices of 0.025 m diameter, taken from the equatorial region of the pomegranate fruit, were vertically stacked in a tube to form a 0.04 m thick sample (Fig. 3.4). This measurement setup provides the in-plane thermal properties of the layered slices as demonstrated in Fig. (3.4 (a)). Assuming the slices to have similar thermal conductivity, Eq. (3.9) gives the thermal conductivity of the composite to be equal to that of the individual slice (Schwarz *et al*., 2009; Costa & Vlassov, 2013; Zhao *et al*., 2016). This method may not capture the resistance effect of the upper most parts of the epicarp which is the natural wax layer. The wax layer may have significantly different thermal resistance. To investigate this, a second test setup with horizontally arranged rectangular (0.04 × 0.035 m) slices was used (Fig. 3.4 (b)). This arrangement provides the cross-plane thermal conductivity as given by Eq. (3.10) (Schwarz *et al*., 2009; Costa & Vlassov, 2013; Zhao *et al*., 2016). Here again, assuming the slices to have identical thermal properties, Eq. (3.10) gives the thermal conductivity of the composite to be equal to that of the individual slice.

$$k_{In-plane} = \frac{\sum_{i=I}^{N} k_i t_i}{\sum_{i=I}^{N} t_i} \tag{3.9}$$

$$k_{Cross-plane} = \frac{\sum_{i=I}^{N} t_i}{\sum_{i=I}^{N} t_i / k_i} \tag{3.10}$$

where t_i is the thickness of given layer and k_i is thermal conductivity of that layer.

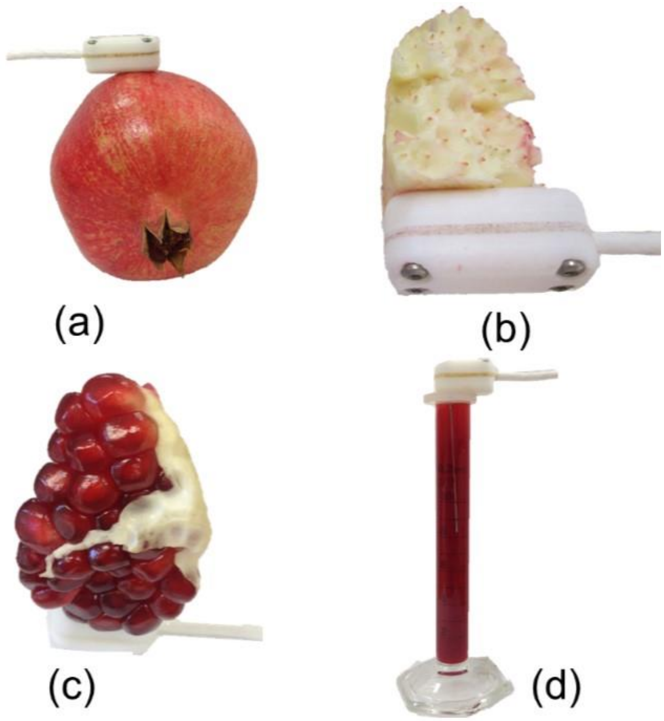

Fig. 3.3 Measurement positions of the thermal needles in (a) whole fruit, (b) mesocarp, (c) arils, and (d) juice

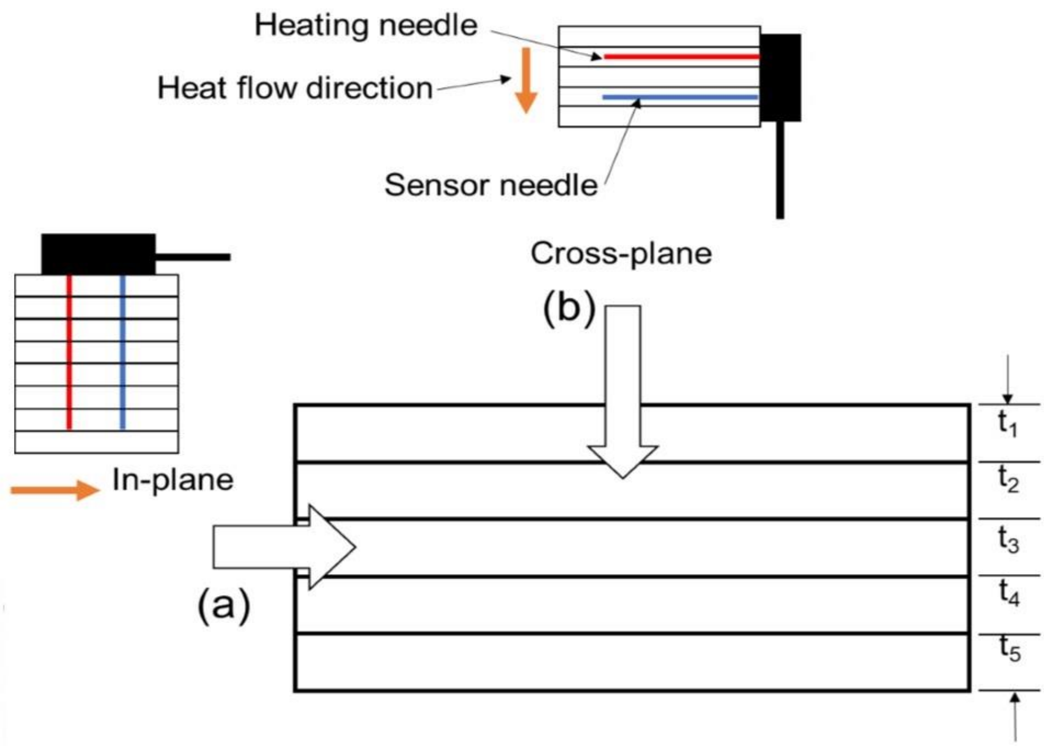

Fig. 3.4 Measurement setups to determine the thermal properties of pomegranate peel (a) in-plane and (b) cross-plane

3.2.5. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 13 (StatSoft, Inc. Oklahoma, USA). Means were separated using Duncan's multiple range tests (Factors: temperature, cultivar and fruit part). The results were presented as mean values (± standard deviation) and means with $p < 0.05$ were considered significant.

3.3. Results and discussions

3.3.1. Fruit density and moisture content

The average volumes of individual 'Wonderful' and 'Acco' pomegranate fruit cultivars were $3.50 \times 10^{-4} \pm 0.9 \times 10^{-5}$ m^3 and $2.73 \times 10^{-4} \pm 5.0 \times 10^{-5}$ m^3, respectively, while the corresponding average weights were 0.35 ± 0.014 kg and 0.28 ± 0.051 kg. The density and moisture content of the whole and parts of the two pomegranate cultivars are listed in Table 3.1. For density, the variance analysis found a statistically insignificant difference between the two cultivars as well as between the different parts of the fruit except for the epicarp. Hence, the average density of pomegranate fruit is 1014.16 ± 21.82 kg m^{-3}. The density of the epicarp (Table 3.1) is, however, significantly lower than the other fruit parts for both 'Acco' and 'Wonderful'. In a similar study, Tehranifar *et al.* (2010) reported densities that vary between 870 ± 40 kg m^{-3} to 970 ± 10 kg m^{-3} for 20 cultivars of pomegranate fruit grown in Iran.

'Wonderful' pomegranate had the moisture content of 76.52 ± 0.63% while that of 'Acco' was 74.05 ± 1.94%. Analysis of variance of the moisture content values obtained showed significant differences ($p < 0.05$) for the epicarp (Table 3.1). The moisture content of the epicarp is 20% less than the other parts of the fruit. As most fruit have moisture contents between 80 and 95% (Sweat, 1974), pomegranate is, therefore, a relatively dry fruit. The moisture content of the two pomegranate cultivars was in reasonably close agreement with those reported by other researchers (Al-Said *et al.*, 2009).

3.3.2. Thermal conductivity

Whole fruit thermal conductivity of 'Acco' and 'Wonderful' pomegranates at 7 °C were 0.499 ± 0.200 W m^{-1} K^{-1} and 0.496 ± 0.024 W m^{-1} K^{-1}, respectively. There was no significant difference between the thermal conductivities of the two cultivars in the temperature range tested (Table 3.2). For both cultivars, thermal conductivity increased with temperature, with a sharp increase from 7–35 °C (Fig. 3.5). This is generally true for fruit (Mohsenin, 1980; Sweat, 1974; Liang *et al.*, 1999; Gharibzahedi *et al.*, 2014; Mamani, 2015) because of the high moisture content of fruit materials. The thermal conductivity of most solids and liquids decreases with increasing temperature, but water is an anomaly because it increases with increasing temperature (Mohsenin, 1980). The average thermal conductivity of the whole fruit, for both cultivars, was 0.55 ± 0.07 W m^{-1} K^{-1}, in the tested temperature range.

Table 3.1 Density and moisture content of the intact (whole) and the different parts of pomegranates fruit (‘Wonderful’ and ‘Acco’)

Cultivar	Fruit part	Density (kg m^{-3})	Moisture content (%)
Wonderful	Whole	986.99 ± 23.82^{a}	76.52 ± 0.63^{a}
	Epicarp	922.54 ± 76.09^{b}	64.00 ± 4.05^{b}
	Mesocarp	950.37 ± 31.15^{a}	76.87 ± 3.40^{a}
	Arils	992.23 ± 63.28^{a}	76.88 ± 1.72^{a}
Acco	Whole	1041.23 ± 18.93^{a}	74.05 ± 1.94^{a}
	Epicarp	915.40 ± 56.25^{b}	57.14 ± 1.32^{b}
	Mesocarp	1025.85 ± 38.00^{a}	70.45 ± 2.54^{a}
	Arils	1063.33 ± 64.09^{a}	76.20 ± 0.62^{a}

Values are means ± standard deviation, values with different letters in one column infer to significant difference ($p < 0.05$)

On average, the thermal conductivity values of the epicarp, mesocarp, and arils were 0.431 ± 0.042 W m^{-1} K^{-1}, 0.395 ± 0.055 W m^{-1} K^{-1}, and 0.497 ± 0.087 W m^{-1} K^{-1}, respectively. The aril part of the fruit generally had higher thermal conductivity values compared to the epicarp and mesocarp, and this could be due to the comparatively higher moisture content of the arils (Table 3.3). Thermal conductivity of the juice was recorded and given in Table 3.4. The average thermal conductivity of pomegranate fruit calculated based on material composition data is 0.52 W m^{-1} K^{-1} (Ambaw *et al*., 2017). This value was estimated from the thermal property models of Choi and Okos (1983) based on pomegranate mass composition of 80.97% moisture, 0.95% protein, 0.30% fat, 16.57% carbohydrate, 0.6% fibre, and 0.61% ash (USDA, 1996). For engineering analysis of a precooling process, accuracies greater than 5% may not be required as error due to other assumptions in the mathematical model (boundary conditions: air temperature, velocities, turbulence and model geometries) would normally exceed the error due to inaccurate thermal property data (Rao *et al*., 2014).

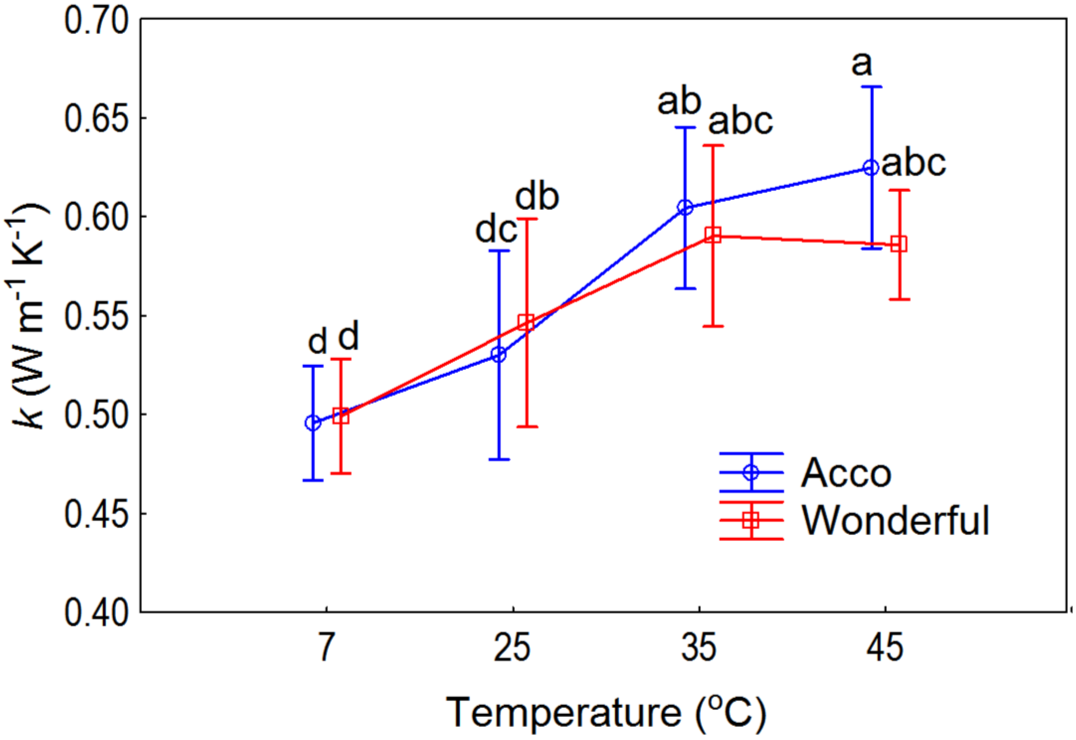

Fig. 3.5 Effect of temperature on the thermal conductivity (*k*) of 'Acco' and 'Wonderful' pomegranates. Vertical bars denote standard deviation of mean. Different letters indicate significance difference ($p <$ 0.05)

3.3.3. Specific heat capacity

Values of specific heat capacity of whole fruit and the different fruit parts are given in Tables 3.2 and 3.3, respectively. The specific heat capacity of 'Acco' varied from 2964.763 ± 369.755 J kg^{-1} K^{-1} to 3371.013 ± 379.359 J kg^{-1} K^{-1} while that of 'Wonderful' varied from 3846.037 ± 302.941 J kg^{-1} K^{-1} to 3198.614 ± 394.128 J kg^{-1} K^{-1}, for temperature ranging from 7–45 °C. Owing to its high moisture content (mc), the aril part of both cultivars had higher specific heat value than the mesocarp and epicarp. 'Acco' showed a more uniform value of specific heat capacity than 'Wonderful' (Table 3.3). There was no observed trend with temperature in the range tested. Cultivar too had no significant effect on the specific heat capacity (Fig. 3.6). The specific heats of the two pomegranate cultivars are relatively lower in comparison to other fruit, at measurement temperature 40 °C and above, Ratti & Mujumdar, (1993) reported 3829 J kg^{-1} K^{-1} for apples at 40 °C, 88% mc, Lozano *et al*. (1979), 3829 J kg^{-1} K^{-1} for Granny smith apples at 40 °C, 88% mc, Ramaswamy & Tung, (1981), 3690 J kg^{-1} K^{-1} for golden delicious at 40 °C, 88% mc, and Sweat, (1994) 3730 J kg^{-1} K^{-1} for pears with 83.8% mc. This may be attributed to the relatively lower moisture content of pomegranate fruit.

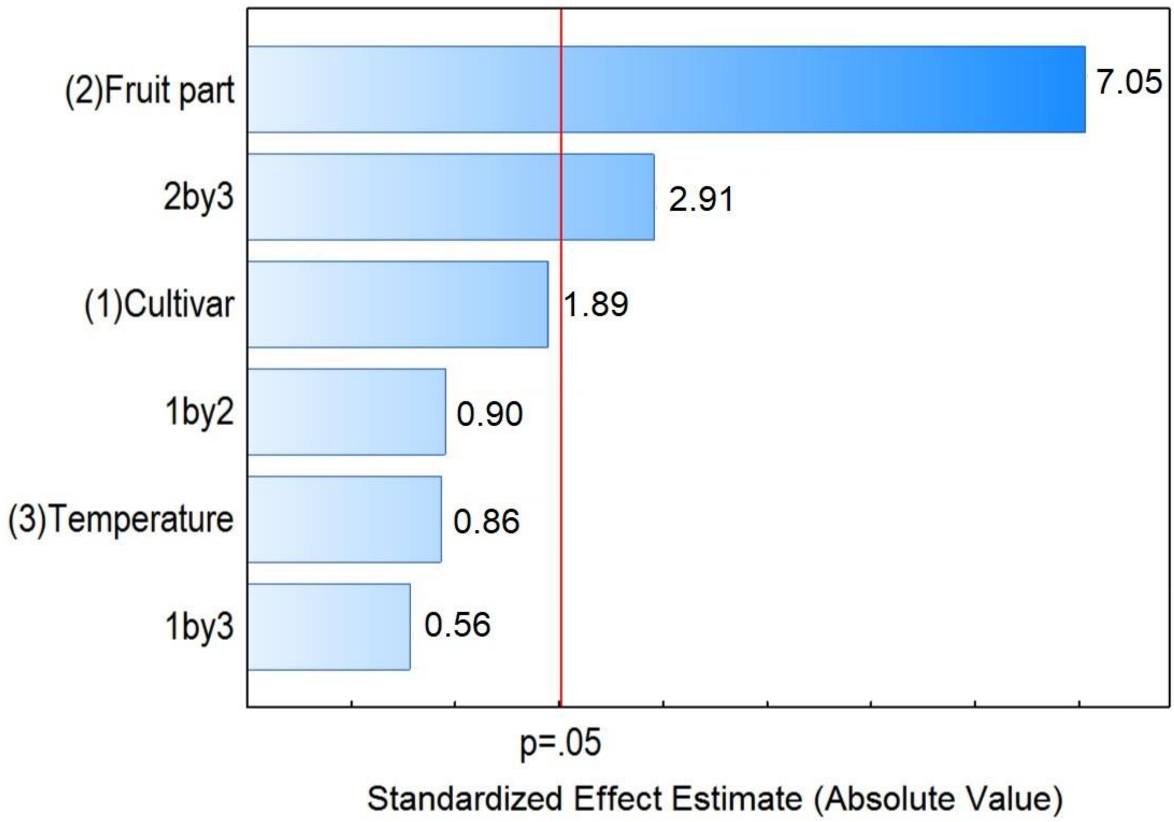

Fig. 3.6 Pareto chart of standardized effects showing the effect of fruit part, temperature, cultivar, and their interaction on the specific heat of pomegranate fruit (‘Acco’ and ‘Wonderful’)

3.3.4. Thermal diffusivity

Thermal diffusivity was not significantly different between the two cultivars (Fig. 3.7). The average thermal diffusivity values of the epicarp, mesocarp and arils were: 1.940 ± 0.366 × 10^{-7} m^2 s^{-1} and 2.047 ± 0.487 × 10^{-7} m^2 s^{-1}; 1.498 ± 0.164 × 10^{-7} m^2 s^{-1} and 1.540 ± 0.133 × 10^{-7} m^2 s^{-1}; and 1.614 ± 0.264 × 10^{-7} m^2 s^{-1} and 1.664 ± 0.408 × 10^{-7} m^2 s^{-1} for ‘Acco’ and ‘Wonderful’, respectively. The lowest thermal diffusivity value (1.369 ± 0.165 × 10^{-7} m^2 s^{-1}) was observed at the lowest temperature (7 °C) (Table 3.2). Contrary to our findings, Zabalaga *et al*. (2016) reported a lower level of dependency of thermal diffusivity with temperature for banana slices (thermal diffusivity ranges between 1.97 × 10^{-7} m^2 s^{-1} and 1.26 × 10^{-7} m^2 s^{-1} between 40 and 60 °C).

In-plane and cross-plane thermal property values of pomegranate peels at 7 °C are given in Table 3.5. Thermal conductivity, specific heat capacity, and thermal diffusivity of the two measurement orientations deviated by less than 5%. This may indicate that the thermal properties of the peel are isotropic. Hence, the heat diffusion can be assumed the same in every direction in the peel.

Table 3.2 Thermal properties of whole ('Wonderful' and 'Acco')

Temp (ºC)	Wonderful			Acco		
	k (W m^{-1} K^{-1})	C_p (J kg^{-1} K^{-1})	α (× 10^{-7} m^2 s^{-1})	k (W m^{-1} K^{-1})	C_p (J kg^{-1} K^{-1})	α (× 10^{-7} m^2 s^{-1})
7	0.499 ± 0.200^{d}	3846.037 ± 302.941^{a}	1.369 ± 0.165^{c}	0.496 ± 0.024^{d}	2964.763 ± 369.755^{b}	1.627 ± 0.196^{ac}
25	0.546 ± 0.008^{bd}	3302.972 ± 431.615^{ab}	1.693 ± 0.206^{ab}	0.530 ± 0.016^{dc}	3201.982 ± 530.142^{ab}	1.617 ± 0.235^{ac}
35	0.590 ± 0.082^{abc}	3877.446 ± 839.927^{a}	1.580 ± 0.316^{bc}	0.604 ± 0.044^{ab}	3141.477 ± 437.944^{ab}	1.872 ± 0.227^{ab}
45	0.591 ± 0.072^{abc}	3198.614 ± 394.128^{b}	1.883 ± 0.192^{a}	0.625 ± 0.014^{a}	3371.013 ± 379.359^{ab}	1.794 ± 0.155^{ab}

Values are means ± standard deviation, values in the two columns of k, C_p, α, respectively, with different letters infer to significance difference ($p<0.05$). k = thermal conductivity, c_p = specific heat capacity, α = thermal diffusivity

Table 3.3 Thermal properties of pomegranate fruit parts ('Wonderful' and 'Acco')

Temp (ºC)	**Fruit part**	**Wonderful**			**Acco**		
		k (W m^{-1} K^{-1})	**C_p (J kg^{-1} K^{-1})**	**α (× 10^{-7} m^2 s^{-1})**	**k (W m^{-1} K^{-1})**	**C_p (J kg^{-1} K^{-1})**	**α (× 10^{-7} m^2 s^{-1})**
7	Epicarp	0.359 ± 0.022^{f}	$2782.535 \pm 350.120^{bcde}$	1.425 ± 0.244^{e}	0.389 ± 0.030^{f}	$2681.888 \pm 135.460^{bcde}$	1.588 ± 0.163^{ef}
	Mesocarp	0.381 ± 0.048^{ef}	$2886.244 \pm 391.426^{bcd}$	1.410 ± 0.229^{e}	$0.352 \pm 0.040^{d-f}$	$2560.803 \pm 231.028^{bcde}$	1.343 ± 0.179^{f}
	Arils	0.421 ± 0.074^{def}	$3101.096 \pm 623.847^{ab}$	1.393 ± 0.255^{e}	0.419 ± 0.047^{bc}	2775.244 ± 298.120^{b}	1.414 ± 0.283^{def}
25	Epicarp	0.414 ± 0.019^{def}	$2317.515 \pm 176.686^{def}$	1.943 ± 0.060^{bcd}	0.425 ± 0.009^{def}	$2830.457 \pm 424.951^{bcde}$	1.660 ± 0.202^{cde}
	Mesocarp	0.448 ± 0.019^{cdef}	$2769.448 \pm 86.282^{bcde}$	1.703 ± 0.102^{cde}	0.375 ± 0.078^{ef}	$2264.464 \pm 73.110^{cdef}$	1.608 ± 0.292^{cde}
	Arils	0.479 ± 0.024^{bcde}	3571.753 ± 426.312^{a}	1.370 ± 0.216^{e}	0.417 ± 0.035^{def}	$2720.698 \pm 236.051^{bc}$	1.450 ± 0.163^{de}
35	Epicarp	0.457 ± 0.040^{cdef}	$2202.615 \pm 205.953^{ef}$	2.250 ± 0.010^{ab}	0.476 ± 0.008^{bcde}	$2357.439 \pm 308.062^{def}$	2.227 ± 0.255^{ab}
	Mesocarp	0.380 ± 0.066^{ef}	$2747.351 \pm 136.789^{bcde}$	1.458 ± 0.273^{de}	0.509 ± 0.034^{bcd}	$2981.917 \pm 106.253^{ab}$	1.667 ± 0.168^{cde}
	Arils	0.575 ± 0.097^{ab}	3598.964 ± 437.399^{a}	1.647 ± 0.469^{cde}	0.467 ± 0.029^{cdef}	$2820.385 \pm 506.898^{ab}$	1.600 ± 0.358^{cde}
45	Epicarp	0.465 ± 0.038^{cdef}	1976.066 ± 242.808^{f}	2.570 ± 0.314^{a}	0.464 ± 0.037^{cdef}	$2265.676 \pm 327.726^{ef}$	2.283 ± 0.503^{ab}
	Mesocarp	0.357 ± 0.002^{f}	$2368.551 \pm 154.677^{def}$	1.590 ± 0.113^{cde}	0.360 ± 0.044^{f}	$2549.106 \pm 142.321^{bcde}$	1.373 ± 0.090^{e}
	Arils	0.655 ± 0.197^{a}	$3048.688 \pm 720.599^{ab}$	2.247 ± 0.760^{ab}	0.541 ± 0.016^{bc}	$2551.419 \pm 53.605^{bcd}$	1.990 ± 0.014^{bc}

Values are means ± standard deviation, values in the two columns of k, C_p, α, respectively, with different letters infer to significance difference ($p<0.05$). k = thermal conductivity, C_p = specific heat capacity, α = thermal diffusivity

Table 3.4 Thermal conductivity of pomegranate fruit juice ('Wonderful' and 'Acco')

Temp (ºC)	Wonderful *k* (W m^{-1} K^{-1})	Acco *k* (W m^{-1} K^{-1})
7	0.455 ± 0.066^{b}	0.586 ± 0.047^{a}
25	0.451 ± 0.067^{b}	0.589 ± 0.079^{a}
35	0.594 ± 0.081^{a}	0.555 ± 0.159^{a}

Values are means ± standard deviation, values with different letters in the two columns infer to significance difference (p<0.05). Readings of *k* at 45 °C were highly erroneous probably due to free convection in liquid samples at high temperature (Decagon Devices, Inc.) hence not included here

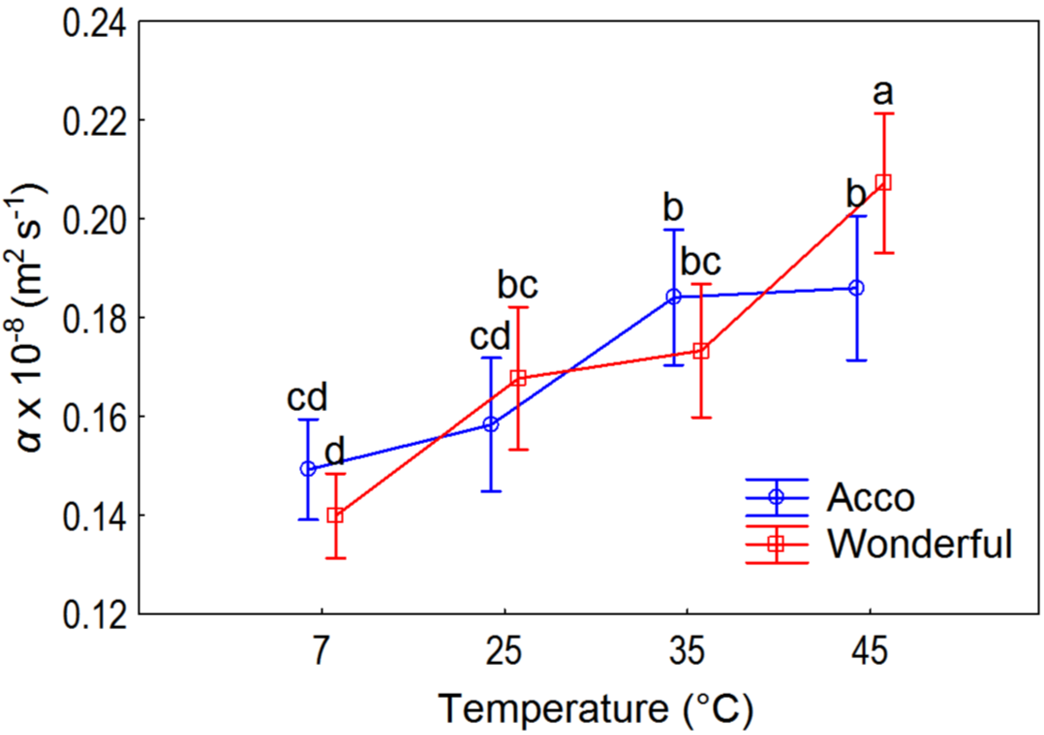

Fig. 3.7 Changes of thermal diffusivity (α) of pomegranate fruit ('Acco' and 'Wonderful') with temperature. Vertical bars denote standard deviation of mean. Different letters indicate significance difference ($p < 0.05$)

Table 3.5 Thermal property values of the in-plane and cross-plane measurements of the stack of pomegranate peels (Epicarp) at 7 °C

Thermal property	In-plane	Cross-plane	Deviation	%
k (W m^{-1} K^{-1})	0.359 ± 0.022	0.374 ± 0.032	-0.015	-4.09
C_p (J kg^{-1} K^{-1})	2782.535 ± 350.120	2698.945 ± 152.470	83.590	3.00
α (x 10^{-7} m^2 s^{-1})	1.425 ± 0.244	1.4260 ± 0.187	-0.001	-0.07

3.4. Conclusion

This study generated data on the thermal properties of ‘Acco’ and ‘Wonderful’ pomegranate fruit cultivars and their individual fruit parts at temperatures 7–45 °C. The thermal properties did not differ between the two studied cultivars. However, there was heterogeneity in the thermal properties of the fruit parts. The aril part of the fruit had higher thermal conductivity and specific heat values. This was attributed to the comparatively higher moisture content of the aril part of the fruit. The thermal properties of intact pomegranate fruit and fruit parts were affected by temperature. The data obtained in this study is important to perform a detailed analysis of fruit internal temperature profile during cooling processes, for instance, by employing a finite element model (FEM). These data are also useful in the design and optimisation of packaging and processes for handling of pomegranate fruit in the cold chain.

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Section B

Declaration by the candidate

With regard to Chapter 4, pages 87–131, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
Compiled and edited manuscript in its entirety throughout the publication process	80

The following co-authors have contributed to Chapter 4, pages 87–131:

Name	e-mail address	Nature of contribution	Extent of contribution (%)
Alemayehu Ambaw	tsige@sun.ac.za	Contributed to the design of the review and edited the document in its entirety throughout the publication process	10
Umezuruike Linus Opara	opara@sun.ac.za	Conceptualised the review and and edited the document in its entirety throughout the publication process	10

Declaration with signature in possession of candidate and supervisor **Signature of candidate**	16/08/2019 **Date**

Declaration by co-authors

The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4, pages 87–131,

2. no other authors contributed to Chapter 4, pages 87–131 besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4, pages 87–131 of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019

Chapter 4

Advances in design and performance evaluation of fresh fruit packaging: A review

Abstract

Packaging is an indispensable unit operation in handling and distribution of fresh fruit. Fruit vary in physical, mechanical, thermal, and metabolic properties, thus, require different postharvest handling tools and practices. Therefore, in order to deliver each fruit in the best form and extend the fruit useful life, fruit packages have to be designed specifically for particular fruit or fruit groups. Postharvest handling practices including different precooling procedures, cold storage, and transportation requirements need fruit packages to have the specific design attributes to protect fruit and deliver quality fruit to the ultimate consumer. This paper thus focussed on package design requirements in the fresh fruit industry and subsequent performance evaluation of the designs. Packages for fresh fruit are designed to enable fast, uniform, and energy efficient cooling of the fruit to minimise deteriorative changes, but also strong enough to withstand conditions of low temperature and high humidity under which most fresh fruit are handled. The review is a valuable input, highlighting the main carton design considerations for fresh fruit in the cold chain, the role of carton vent-holes, materials used, carton performance evaluation, and how packaging contributes to overall fresh fruit quality.

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*Under review:

Mukama, M., Ambaw, A. & Opara, U.L. (2019). Advances in design and performance evaluation of fresh fruit packaging: A review. *Food Packaging and Shelf Life*

4.1. Introduction

Packaging is a key food processing unit operation serving functions of containment, protection, preservation, storage, and distribution of food (Robertson, 2013). Globally, over 67% of the volume of fruit production is consumed fresh (Ladaniya, 2008). The fresh fruit market employs different package designs, including punnets, corrugated fibreboard cartons (CFC), plastic crates, plastic, and woven nets. These are made from different materials, including wood, jute, plastic, metal, and paper (Ladaniya, 2008). However, corrugated paperboard/fibreboard cartons are the most widely used in fresh fruit markets (Opara & Mditshwa, 2013; Berry *et al*., 2015).

The cartons handle fruit in single or multilayers separated with trays or air-bubble entrapped films (Opara, 2011; Pathare *et al*., 2012; Opara & Mditshwa, 2013). Fresh fruit packages are designed with vent-holes that enhance cooling by enabling contact between the fruit and cold air streams and outflow of respiration heat from produce (Zou *et al*., 2006; Opara & Mditshwa, 2013; Berry *et al*., 2017). However, poorly designed cartons with inadequate ventilation, vent-hole misalignment on pallet stacks, and use of internal packages, for example, polyliner bags significantly reduces the airflow distribution among fruit in ventilated packaging and negatively impacts fruit cooling rates (Ngcobo *et al*., 2013; O'Sullivan *et al*., 2016; Mukama *et al*., 2017). Nevertheless, the polyliners were found to minimize moisture loss and associated shrivelling in pomegranate fruit (Mphalele *et al*., 2016). In a study by Mphalele *et al*. (2016), commercially ripe pomegranate fruit packaged in ventilated cartons with polyliner (passive modified atmosphere packaging) lost significantly lower amount of water in comparison to non polyliner packaged fruit. Shrivelled fruit loses commercial value due to reduced sellable weight and visual appeal.

Fresh fruit packages handling involves palletization and stacking under storage and transportation. This eases the handling and movement of the packaged fruit (Chen *et al*., 2011) and reduces physical injuries to fruit through reduced individual carton handling. It is thus necessary that compression tests are undertaken on all new designs to determine suitability to this practice (Berry *et al*., 2017). In addition, drop, impact and burst tests, as well as water absorption capacity—Cobb value, for the case of wettable materials give further information on carton mechanical integrity (Pathare & Opara, 2014). Design of vents on the carton walls needs to be done with consideration of reduced airflow resistance, energy efficiency, fast and uniform cooling of the produce, as well as mechanical integrity of stack in the cold chain (Han *et al*., 2015; Fadiji *et al*., 2016; Berry *et al*., 2017). De Castro *et al*. (2004) reported that increase in carton wall vent area ratio beyond 8% does not give significant increase in fruit cooling rates, a similar observation (7%) made by Delele *et al*. (2013a). Normally, vent area ratio of 5% enables sufficient airflow within the packaged produce (Thompson *et al*., 2008). The vents also need to align on stacking to facilitate the cross flow of cooling air between packages for efficient cooling (Berry *et al*., 2017). In terms of mechanical integrity, Fadiji *et al*. (2016a) reported better retention of mechanical strength by rectangular vent-holes compared to circular ones and increases in vent area and height reduced package mechanical strength.

Fruit are perishable products with varying levels of perishability depending on the type of fruit and surrounding conditions. High respiration rates in climacteric fruit, dehydration, oxidation and microbial decay are some of the major challenges facing the horticultural industry, affecting the supply of raw and fresh-cut fruit, that are otherwise, on an ever-increasing demand (Ladaniya, 2008; Robertson, 2010; Aindongo *et al*., 2014). Therefore, optimal packaging and cold chain maintenance are critical postharvest operations to minimize losses and wastage. Proper cold chain operations begin with harvesting fruit at the coldest times of the day, followed by precooling, with intent to rapidly remove field heat after harvest (Ambaw *et al*., 2017; Berry *et al*., 2017). Precooling minimizes physical and biological changes of harvested produce during postharvest handling (Ravindra & Goswami, 2008). Once the produce attains the storage temperature, it is stored in cold rooms or reefers in transit. Finally, produce should be handled at recommended temperature during display at a warehouse or retail stores, as well as in consumer households.

Packaging science and technologies in the fruit industry have been discussed extensively by a number of authors; structural design of CFC (Pathare & Opara, 2014), fresh produce package performance evaluation (Defraeye *et al*., 2015a), use of computational fluid dynamics in fruit storage facilities (Ambaw *et al*., 2013a), airflow measurement techniques in fruit forced air cooling (O'Sullivan *et al*., 2014), mechanical design and performance testing of CFC (Fadiji *et al*., 2018a, b). However, fruit are naturally variable materials with unique properties that may hardly be generalised, thus special considerations are often required. In order to deliver fresh fruit to the consumer at its best quality, the packaging should facilitate cold chain handling while also reliably providing mechanical protection to the produce against mechanical forces. This review provides an overview of the design considerations of cartons used in the fresh fruit industry, with emphasis on corrugated fibreboard cartons, a description of fruit cold chain and the evaluation process of the designed cartons.

4.2. Packaging in the fresh fruit industry

4.2.1. The functions of packaging

Fruit consumption is on an ever-increasing trend due to the scientifically acclaimed health benefits of fresh fruit consumption (Steinmetz & Potter, 1996). Following harvest, fruit continue to respire, breaking down stored sugars which negatively affects their quality as the replenishment from the parent plant is cut off. These deteriorative metabolic processes are temperature driven and thus quality deterioration is high when fruit are handled at high temperatures (Caleb *et al*., 2012). Because of their relatively small size, fruit are normally put into containers to ease handling and movement. Containers made from different materials– wood, paper, plastic, glass are employed in the fruit industry and are designed to keep produce fresh. Containers allow quick handling and marketing, protects the commodity by reducing mechanical loads such as drop, impact, vibration and compression loads, protect the produce from contaminants and reduce water loss.

In the various stages of cold chain management including distribution, fruit endure different types and combinations of mechanical loads. These loads may cause injuries like cuts, bruises, abrasions, and punctures. The level and severity of these losses depend on the energy inputs to the package during transport and handling, and the way in which the energy is dissipated within the package. Table 4.1 summarises the different mechanical forces, their occurrence and the injury they cause on fruit.

Among the various mechanical forces, impact has been recognized as the most crucial cause of damage (bruising) in fruits (Pang *et al*., 1992). Excessive compression also causes bruising, as do repeated impacts. Bruising appears as a result of vibration, impacts, and compressions of the fruits against other fruits, parts of the trees, containers, parts of any grading and treatment machinery, and on any un-cushioned surfaces. Severity of damage to the fruit is primarily related to: (i) height of fall; (ii) initial velocity; (iii) number of impacts; (iv) type and size of impact surface; and (v) physical properties of the fruit, related or not to maturity. Hence, produce container must be properly designed to enclose the produce in convenient units for handling and distribution and protect the produce from mechanical damage.

Table 4.1 Summary of mechanical forces, their occurrence and the injury they cause on the fruit

Mechanical force	**Occurrences**	**References**
Impact	Dropping the product onto a hard surface Dropping the product into the back of a car Excessive drops during loading and unloading Suddenly stopping or accelerating a vehicle	Holt & Schoorl, (1977); Schoorl & Holt, (1980); Peleg, (1981, 1985); Jarimopas *et al*., (1984, 2007); Chen & Yazdani, (1991); Pang *et al*. (1992); Bajema & Hyde, (1998); Ragni & Berardinelli, (2001); Fadiji *et al*. (2016b); Ahmadi *et al*. (2010, 2012); Opara & Pathare, (2014); Hussein *et al*. (2019)
Vibration or abrasion	Vehicles with small wheels and bad shock-absorbers Weak crates Bad roads Transmission vibration	Darmawati & Yulianti (2009); Vursavus & Ozguven, (2004); Chonhenchob & Singh (2005); Jarimopas *et al*. (2007); Chonhenchob *et al*. (2009); Park *et al*. (2011); Eissa *et al*. (2012); Fadiji *et al*. (2016c)
Compression injuries	Over-packing of crates and boxes Too high stacking of crates Weak packaging	Urbanik, (2001); Han & Park (2007); Navaranjan *et al*., (2013); Fadiji *et al*. (2016a, 2018a); Berry *et al*. (2017)
Puncturing injuries	Nails or splinters from the crate or box Fingers or nails of a person Other crates, fork-lifts, etc. Hard and sharp stalks of fruit	Tim *et al*. (1996); Spotts *et al*. (1998); Rudra *et al*. (2013)

4.2.2. Types of packaging for produce handling

In global fruit trade, corrugated fibreboard cartons and reusable plastic containers (RPC) are frequently used as shipping packages. Comparatively, the use of CFC cartons surpasses RPC (Opara & Mditshwa, 2013; Defraeye *et al*., 2015a) due to their lightweight, completely recyclable, biodegradable, and more cost-effective than other materials (Pathare & Opara, 2014). Corrugated cardboard materials are also good in damping mechanical impacts and vibration, which are sources of damage on fruit. In the south African pome fruit industry, CFC are the most commonly used cartons (Berry *et al*., 2015), and over 90% of fresh fruit packaging in the USA makes use of CFC (Little & Holmes, 2000). RPC are made from recyclable plastic material, mostly polyethylene that is moulded to the desired shape, size and ventilation (McGrath, 1993). RPC for fresh produce movement is ideal in close and local markets where the logistics of return will be easily managed but may be difficult in international trade where fruit are shipped for weeks to the destination markets.

The stage of fruit handling governs the size of container to use. Bulk packages moved by forklifts are handled using wooden bins (Fig. 4.1 (a) and (b)) or plastic (Fig. 4.1 (c) and (d)). These packages weigh as much as 550 kg (Tim *et al*., 1996). Depending on the size of the fruit bins can be designed with maximum venting (Fig. 4.1 (a) and (c)) or closed with reduced ventilation (Fig. 4.1(b) and (d)). Packages of produce commonly handled by hand are usually limited to 25 kg in a wooden, plastic or corrugated fibreboard cartons (Fig. 4.1 (e) to (h)).

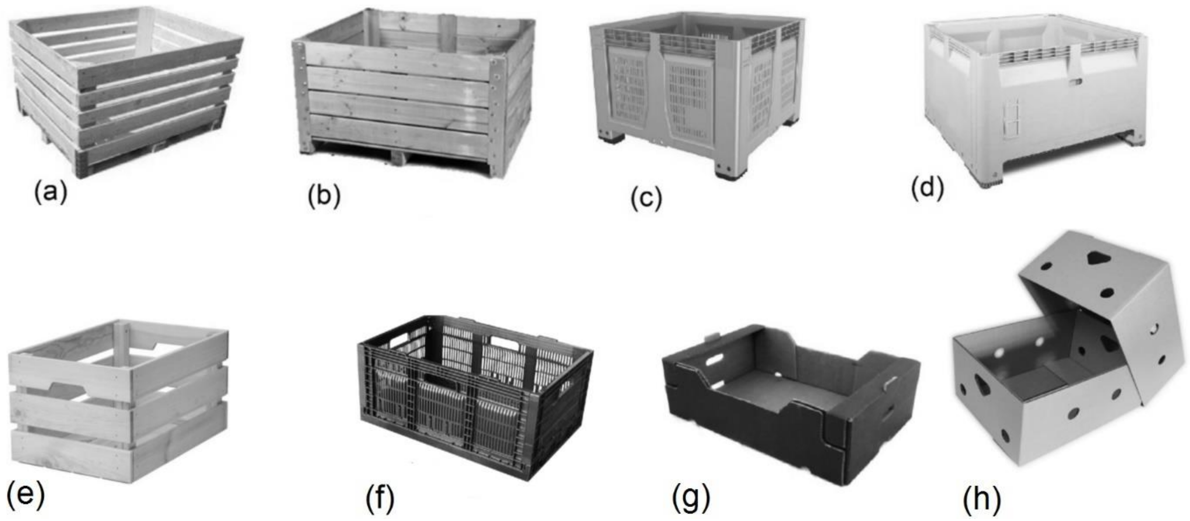

Fig. 4.1 Types of fruit containers. (Top row) cartons used mostly on farms and moved by forklifts (top row): (a) wooden bulk bin with more open sides, (b) wooden bulk bin with closed sides, (c) reusable vented plastic bulk bins, (d) reusable closed plastic bulk bin. (Bottom row) cartons commonly used to handle produce by hand: (e) wooden crates, (f) reusable plastic container, (g) display corrugated fibreboard cartons and (h) telescopic corrugated fibreboard cartons

Packaging footprints need to conform to the dimensions of the pallet standard to be used (Fig. 4.2). The dimensions of the pallet depend on the standard required in the market. For instance, the ISO2 standard, (W × L) 1.0 × 1.2 m (Fig. 4.2 (a) to (c)) and the ISO1 standard, 0.8 × 1.2 m (Fig. 4.2 (d)) standards are frequently used in Europe and Asia as presented in ISO Standard 6780: Flat pallets for intercontinental materials handling-Principal dimensions and tolerances.

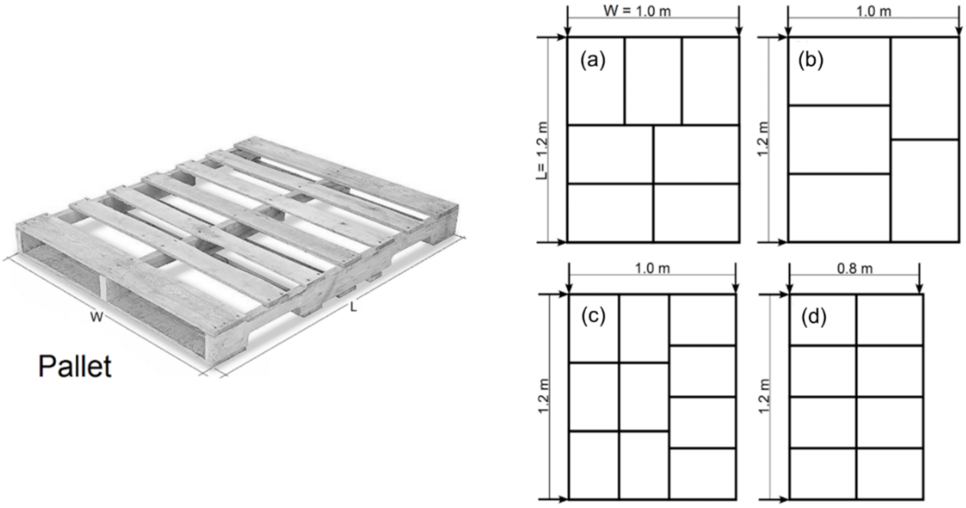

Fig. 4.2 Representation of a typical pallet structure. The value of width (W) and length (L) specifications depends on standards as shown in the schematic of stacking patterns on the ISO2 standard ((a) to (c)) and ISO1 standard (d) pallets

Fruit packaging involves use of more than a single material to package fruit for the market. This is referred to as multiscale packaging (Fig. 4.3) (Ngcobo *et al*., 2013; Berry *et al*., 2015). Additionally, the individual cartons are bulked into stacks that may then be unitised into a reefer in transit. Thus, analysis of the cooling characteristics and performance parameters in the fruit cold chain needs a multiparameter approach to take into consideration the different scales, from the individual fruit properties to properties of a fully stacked refrigerated room/reefer (Ho *et al*., 2013; Berry *et al*., 2016, 2017). This multiscale approach studies material behaviours at different spatial scales and provides a more comprehensive performance characteristics of the system.

Fig. 4.3 Photographs showing hierarchical packaging levels in a pomegranate fruit multiscale packaging perspective: (a) Internal packaging, (b) CFC carton unit (c) Pallet stacks (d) refrigerated container. Superscripts 2, 3, 4, 5 indicate the different levels of scale

4.2.3. Structural requirements of fruit packaging

Packaging aims to increase the cushioning and damping of impact, compression and vibration forces. Proper design and implementation of packages involves measuring and modelling of mechanical forces and the response of the packaging material and the biological tissues to loading. This problem is basically in the field of solid mechanics that studies the behaviour of solid materials, especially their motion and deformation under the action of forces, temperature changes, and other external or internal agents. Simultaneously, the effect of package design on the produce cooling rate and cooling uniformity and the accompanying energy requirements are also important performance requirements.

A packaging carton should have enough vent-holes to facilitate the thermal exchange between the produce and the cooling air. On the other hand, vent-holes cause reduction in the mechanical strength of the package. Depending on the material of construction, achieving sufficient ventilation and yet be strong enough to prevent collapse can be challenging. It is possible to provide high vent-hole proportion for wooden or plastic materials (Vigneault & Goyette, 2002). However, these materials have many disadvantages that far outweigh the advantages. Wooden materials may be chipped or broken creating sharp edges that may cause severe mechanical damage to the fruit (Tim *et al*., 1996). Additionally, the use of wooden material has negative environmental impact. Rigid plastic packages are not cost effective and are environmentally unfriendly. CFCs are preferred due to their lightweight, high strength low weight ratio, the cartons are biodegradable, recyclable, and pose least damage to the environment. However, the use of CFC requires careful optimization of the mechanical and thermal performances (Opara & Fadiji, 2018).

CFC is made from three or more layers of paperboard with a corrugated core (fluting) and flat faces (linerboard) on one or either sides (Fig. 4.4 (a)). The linerboards are made of Kraft paper of varying thickness. Kraft paper is strong heavy-duty paper from sulphate pulp made from soft woods with grammage 70–300 g m^{-2} and tensile strengths ranging from 2.45–11.28 kN m^{-1} (Kirwan, 2008). Flutings are linerboards that are corrugated using "flute lamination machines" or "corrugators". The flutings and liners are sandwiched using starch-based adhesives to form single to multiple layer boards depending on the required strength (Biancolini, 2005; Fadiji *et al*., 2016a). While flutings provide shear stiffness, the liners provide bending stiffness (Fadiji *et al*., 2018b). Paperboard is orthotropic in nature with 3 main directions that have different mechanical properties: (a) machine direction or roll press direction (MD), perpendicular to machine or cross direction (CD), and the out of plane or thickness direction (ZD) (Fig. 4.4) (Makela & Ostlund, 2003; Fadiji *et al*., 2018b).

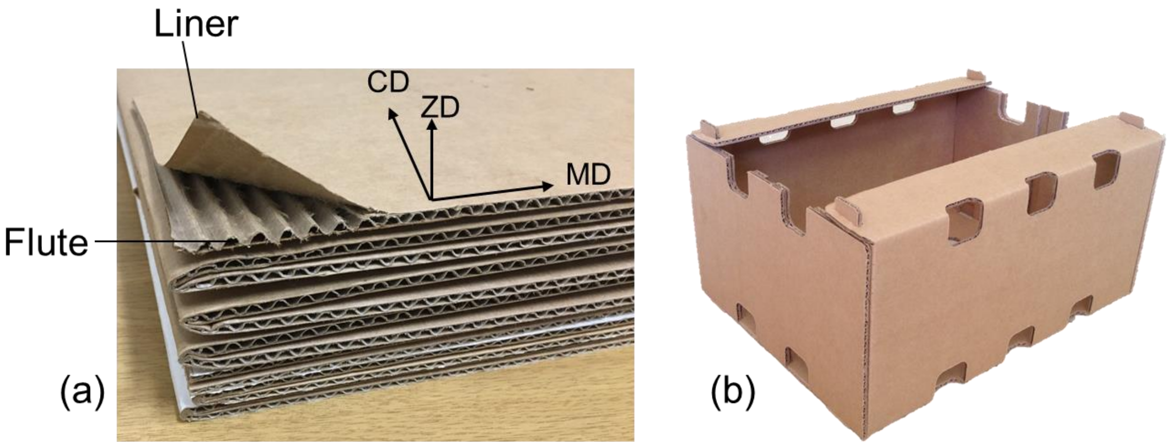

Fig. 4.4 Schematic showing (a) basic geometric structure of corrugated fibreboard (co-ordinates: ZD is the thickness direction, CD is the cross direction and MD is the machine direction, (b) fully made ventilated corrugated fibreboard carton

A challenge of using CFC is ensuring cartons maintain their mechanical strength under cold chain conditions and over extended durations of handling and storage. Factors that can negatively influence carton integrity include high humidity environments, large compression forces (due to pallet stacking), and the configuration of vent-holes (Ngcobo *et al*., 2013; Fadiji *et al*., 2016a, 2018a; Berry *et al*., 2017, 2019). Packaging designers thus need to maintain a strict balance between minimizing cost (materials) and packaging performance (mechanical strength and cooling).

4.3. Vent-hole design

4.3.1. Carton-vents for effective cooling of produce

Carton vents play a critical role in the fresh fruit industry. They aid airflow in the cold chain handling of fruit and remove heat of respiration build up from packaged fruit (Pathare *et al*., 2012). The vents are the “access gates” for the cooling air to the fruit. Vents also ultimately save on the amount of materials used in carton manufacture because the cut-out portions form raw materials for other cartons (Chen *et al*., 2011; Pathare & Opara, 2014).

Precooling is the quick removal of the field heat shortly after the harvest of a crop. The tunnel horizontal airflow system (Fig 4.5 (a)) is the most common FAC arrangement (Boyette, *et al*., 1996; Aswaney, 2007). The top and back sides of the tunnel are covered by cloth or plastic sheet. At the front end of the tunnel, a fan is mounted to pull chilly air through the stack to achieve rapid airflow required to increase the produce cooling rate and reduce cooling time (Fig. 4.5 (b)). Practically, the precooling process continues till 88% of the original temperature difference is removed. This is according to the industrially important characteristic precooling time, called 7/8th cooling time (Boyette, *et al.*, 1996), which is the time required to remove 7/8th of the field heat from the crop (Fig. 4.5 (b)). The horizontal flow of chilled air through the stacked produce is greatly influenced by the vent-hole design (area, shape, number, and position) of the containers, the carton arrangement, the thermophysical properties of the produce, the fruit-stacking pattern within the package, and the ambient conditions; which determines the rate and uniformity of cooling.

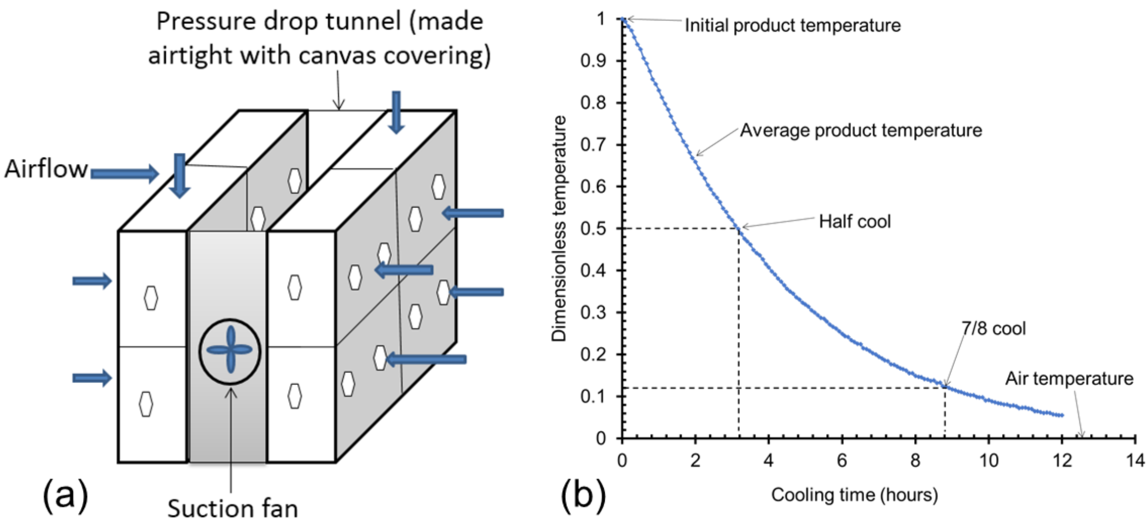

Fig. 4.5 Forced air cooling (FAC) (a) FAC tunnel/carton setup, and (b) typical cooling curve of a product

There have been several studies published showing carton ventilation designs for different fruit types (De Castro *et al* 2005a, b; Delele *et al.*, 2013a, b; Defraeye *et al.*, 2014; Berry *et al.*, 2016; Fadiji *et al.*, 2016a; Berry *et al.*, 2017). These studies highlighted the significance of adequate ventilation to aid the cooling airflow and the limitation of the mechanical integrity of especially CFC unlike RPC. The vent-holes cause material loss that compromise strength and stability of cartons (Fadiji *et al.*, 2016a). Proper package designs not only consider the vent area, but the size, shape, and position of these vents on the carton (Fig. 4.6) as well as presence of internal packages. These have also been found to affect the airflow and mechanical integrity of CFC (Pathare *et al.*, 2012; Berry *et al.*, 2016; Fadiji *et al.*, 2016a).

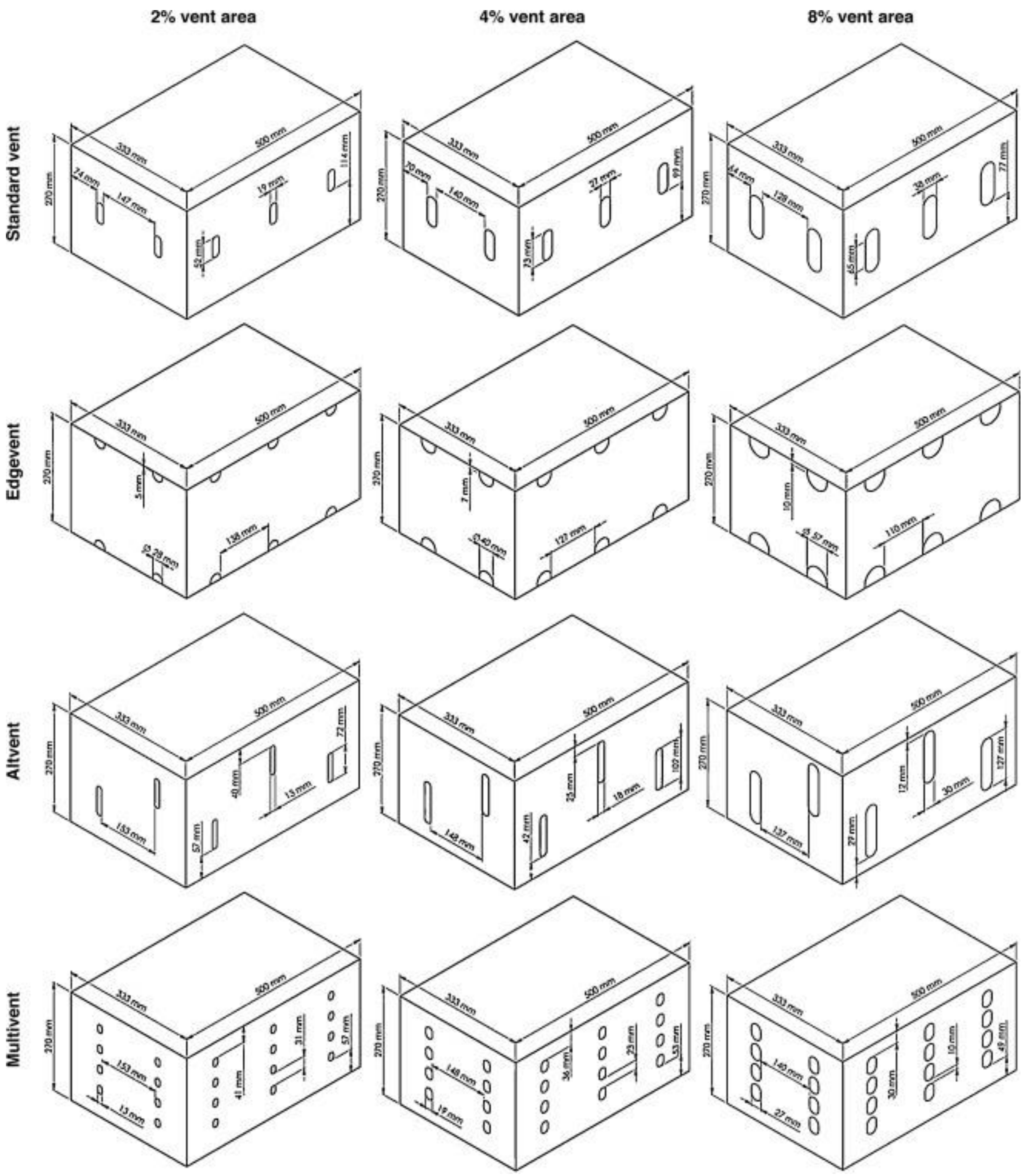

Fig. 4.6 Schematic showing cartons with different vent positions, number, shapes and size for a similar vent area (Berry *et al*., 2017)

Extensive work done on fruit packaging shows that improvement in package vent design improves cooling rates, quality of the produce, and lowers the pressure drop, hence the energy expenditure of produce cooling process (De Castro *et al*., 2004; De Castro *et al*., 2005a, b; Delele *et al*., 2013a, b, c; Defraeye *et al*., 2014; Berry *et al*., 2016; Fadiji *et al*., 2016a; Berry *et al*., 2016; 2017; Mukama *et al*., 2017). Cartons with total ventilation area between 8–16% cool fruit most efficiently (De castro *et al*., 2015a) and a minimum open wall ventilation area of 5–6% is recommended for effective airflow within packages (Mitchel, 1992; Thompson *et al*., 2008). In a study to test the compression strength of cartons as a function of shape, size, and location of vent-holes, Han & Park (2007) recommended to practice vertical oblong vents symmetrically positioned within a certain extent of distance to the right and left from the centre. However, studies by Baird *et al*. (1999) and Delele *et al*. (2013a) reported that cooling efficiency is mostly a function of the vent area, and that the shape of vent-holes plays no significant role on the cooling rate. Shape, orientation, position, and size of vents mostly affects the mechanical integrity of the CFC cartons.

Fruit packaging may use internal package components (trays, punnets, polyliners, moisture sheets, SO_2 sheets, etc.) that play additional roles like minimising fruit moisture loss, modifying fruit environment, etc. (Ngcobo *et al*., 2013; Mukama *et al*., 2019). Therefore, vent-hole distribution should be in tandem with the characteristics and design of these internal packages (Anderson *et al*., 2013; Mukama *et al*., 2019). Global trade of fruit involves pallet stacking during precooling, transportation, and storage of fruit. Alignment of the vent-holes in the stacks (Fig. 4.7) is important to allow uniform flow of air within the stack (Tutar *et al*., 2009: Ambaw *et al*., 2017).

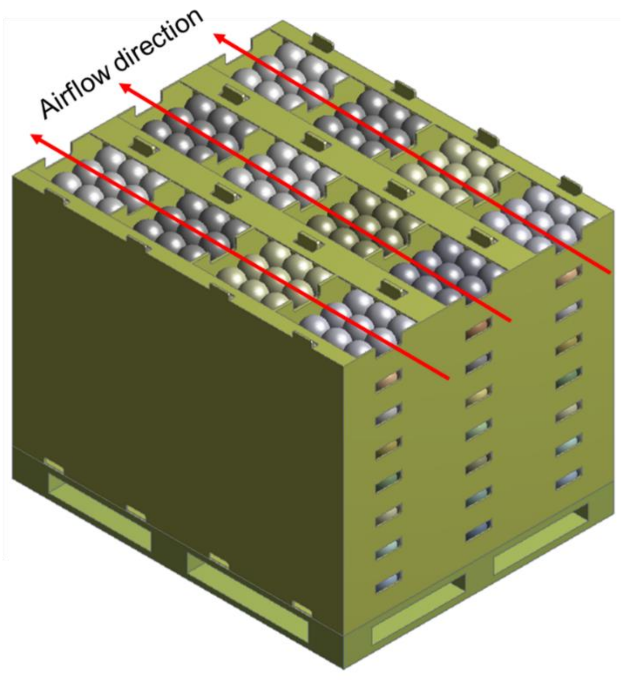

Fig. 4.7 Schematic showing vent-hole alignment in a stack of CFC cartons in the airflow direction

4.3.2. Cold storage rooms

A cold room is characterised by constant circulation of cold air at a set temperature within a room in which fruit is stacked. After the temperature of fruit has been rapidly brought down in the precooling operation, fruit are moved into cold storage rooms awaiting transportation and distribution. The capacity of fans should match the size of the cold room to prevent creation of warm spots when the rooms are packed with produce (Amos, 2005; O'Sullivan *et al.*, 2014). Amos (2005) observed an uneven airflow distribution in cold room packed with produce in bins. They reported high air speeds on top bin layers and bin sides as opposed to centrally stacked bins that received much lower airflow speeds. Cold rooms serve as storage and preservation spaces for fruit before market distribution and in anticipation for offseason periods. In addition to temperature, storage room relative humidity management is also important especially for fruit that lose moisture easily to minimise weight loss and shrivel (Ngcobo *et al.*, 2013; Mukama *et al.*, 2019). Just like in the precooling operation, package design, and stacking arrangements affect airflow (Fig. 4.8) (Johnston, 1994), playing a big role in the maintenance of fruit temperature under cold storage.

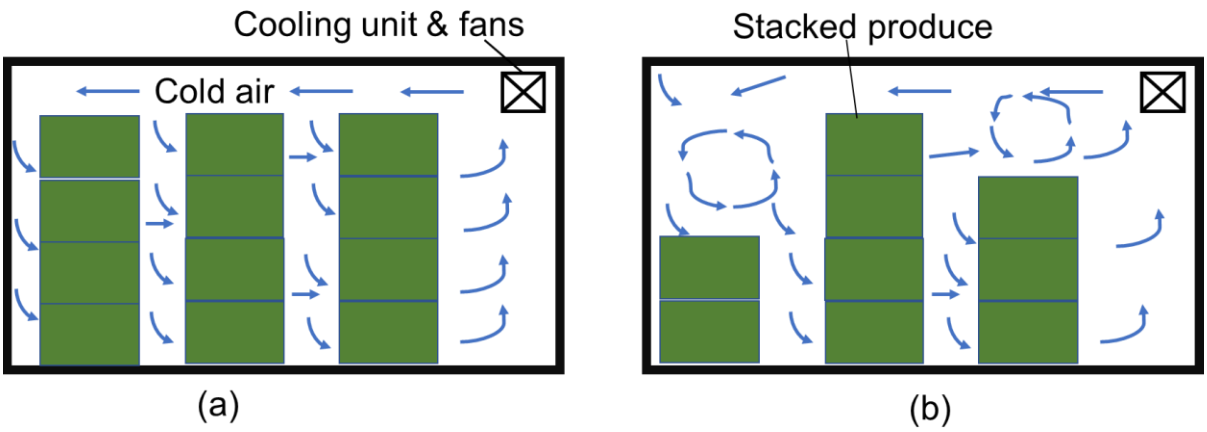

Fig. 4.8 Schematic showing cold storage room (a) uniform airflow distribution when stack heights are uniform, and (b) uneven distribution of airflow due to uneven stack heights

4.3.3. Refrigerated transport

In maintaining the fruit cold chain, fruit is transported in refrigerated trucks and shipped in refrigerated containers (reefers) to the destination markets. Refrigerated transport trailers and reefers use vertical delivery to keep produce cool in transit (O'Sullivan *et al.*, 2014; Getahun *et al.*, 2018). In refrigerated containers, from the refrigeration unit, air is blown through floor gratings, then vertically through the fruit stacks (in two rows) via vent-holes and then back to the refrigeration unit through the ceiling (Smale, 2004; Getahun *et al*. 2017a, b, 2018) (Fig.

4.9). Refrigerated transport, especially on the roads is constrained by vibrational forces that could lead to mechanical damage of fresh fruit (Sittipod *et al*., 2009; Fadiji *et al*., 2016b). Several studies have studied packaging designs with the goal of minimising the effects of these vibrational forces which are augmented by poor road surfaces especially in developing countries (Chonhenchob & Singh, 2005; Jarimopas *et al*., 2007; Jarimopas *et al*., 2008; Darmawati & Yulianti, 2009). Most authors suggested using trays and cushions between individual fruit prone to rubbing against each other like papaya, magosteen, etc. (Chonhenchob & Singh, 2005). The distance travelled, load, truck suspension, travelling speed, and number of axles also affect the vibration of the refrigerated truck (Berardinelli *et al*., 2005; Idah *et al*., 2012; Pathare & Opara, 2014).

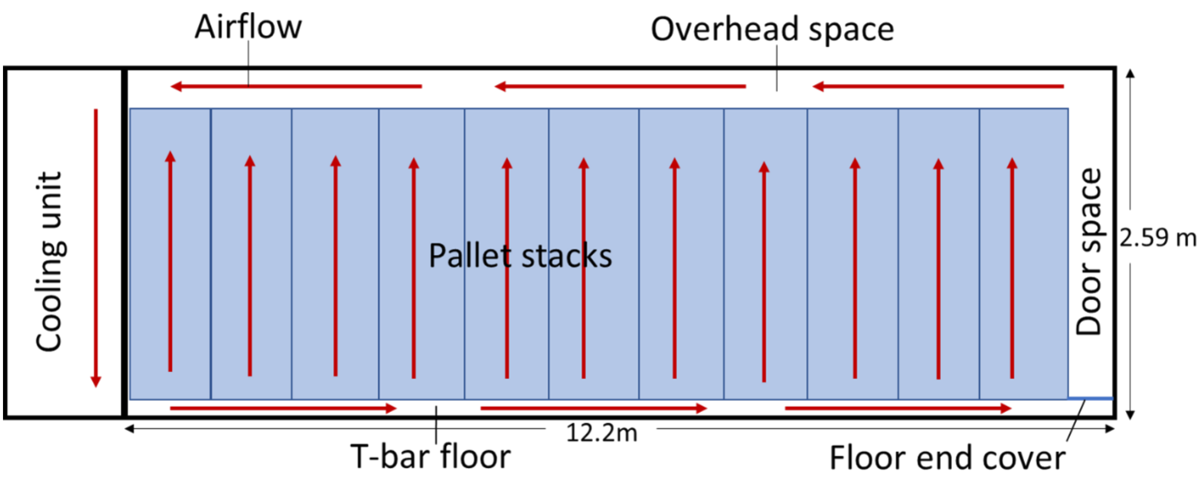

Fig. 4.9 Schematic showing airflow paths through pallet stacks in a standard 40-ft refrigerated container. The floor end cover helps prevent airflow short-circuiting away from carton stacks

Refrigerated containers are designed to keep produce cool and minimise moisture loss. They thus have limited airflow rate and cooling capacity (Thompson *et al*., 2008). In keeping the produce cool during the long-haul transport, there is need for airflow distribution within the pallet stacks (Moureh *et al*., 2009; Getahun *et al*., 2017a, b). Pallet compactness, inadequate vertical vent area (Fig. 4.10), poor carton vent-hole alignment within the stacks could result in stagnant and hot air zones within the stack negatively affecting overall fruit quality (Smale *et al*., 2006; Getahun *et al*., 2017b, Moureh *et al*., 2009). Stacking configurations that partially or fully cover carton bottom vent-holes with slats on the wooden pallets limit vertical airflow within refrigerated containers (Defraeye *et al*., 2016; Getahun *et al*., 2017b). Moureh *et al*. (2009) suggested the use of air ducts within the container releasing air over the top of produce at three positions along the length of truck. This helps reduce possibilities of chilling injury to fruit at front that may receive higher flow rates than intended due to short-circuiting of airflow over the whole stack as a result of poor vent design and stacking. Therefore, carton design for transporting fruit in reefers should enable uniform and easy vertical airflow. Getahun *et al*. (2017a) analysed airflow and heat transfer in a fruit packed reefer using CFD. The authors observed high heterogeneous cooling due to absence of bottom vent-holes to enable top-bottom air circulation on the studied apple carton. On addition of vent-holes (3.5%) on the bottom face of the same carton (open top), Getahun *et al*. (2017b) observed reduced vertical airflow resistance and a 37% reduction in the apple cooling time (SECT) (Fig. 4.10).

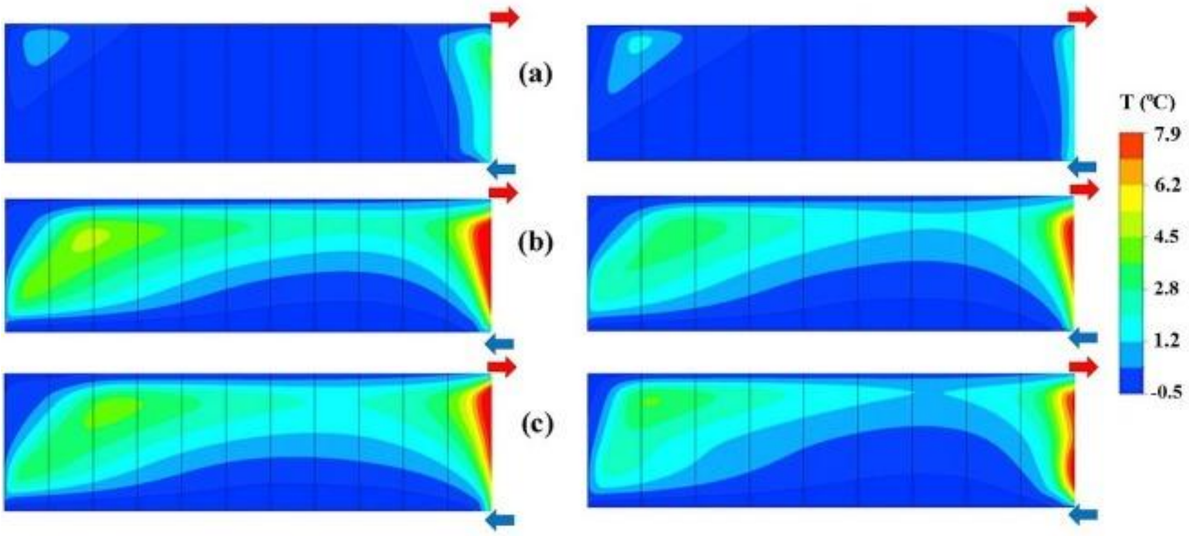

Fig. 4.10 Schematic showing vertical plane temperature distribution in a refrigerated container after 72 h of cooling: row 1 (left) and row 2 (right), with (a) carton with 3.5% bottom ventilation area, (b) carton with 0.25% bottom ventilation area, and (c) carton with 0% bottom ventilation area (Getahun *et al.*, 2017b)

A number of studies have explored loading fruit warm (ambient loading) with intent to cool the fruit during the long-haul transport in reefers (Jedermann *et al*., 2013, 2014; Defraeye *et al*., 2015b, c, 2016; Han *et al*., 2016). Findings are promising, which could save on time and costs in the handling process, however, the envisaged cooling rates are not currently achievable in practice due to low airflow rates characteristic in containers, airflow short-circuiting within gaps in container, hence slow fruit cooling (Defraeye *et al*., 2015c), and gross cooling heterogeneity within carton and stacks (Defraeye *et al*., 2015b). This practice may therefore work for resilient fruit like banana fruit, grapefruit, Valencia oranges, but not fruit sensitive to physiological disorders and decay (Jedermann *et al*., 2013; 2014; Defraeye *et al*., 2015c). Defraeye *et al*. (2016) investigated the possibility of precooling citrus fruit in the reefer in transit. They investigated the normal vertical airflow in the container and two novel airflow configurations: the channelling configuration that reduced airflow by-pass between pallets and the horizontal configuration. The normal vertical airflow and channelling configuration cooled the citrus down to seven eighths cooling time in 3 days. The fruit in the channelling configuration lost lesser moisture and were of better quality in comparison to the normal air delivery and horizontal channelling that performed worst in terms of cooling time and citrus fruit quality. To further protect fruit under transportation, shipping containers may be smeared with waterproof adhesives to minimise possible ingress of moisture into the container which may reduce the mechanical integrity of CFC (Ladaniya, 2008).

4.4. Mechanical design of ventilated packages

4.4.1. Mechanical loads

The stacking practice used in fresh fruit handling requires the necessary structural ability of the cartons to move produce without buckling under the weight of the fruit. In the stack, the bottom cartons experience the greatest load (compression force) which depends on the stack height and weight of the fruit packaged, as well as dynamic load from vibration during transit (Beldie *et al*., 2001). The stacking strength of the carton is a function of the edgewise compression resistance and bending stiffness of the CFC (Urbanik, 2001; Navaranjan *et al*., 2013). Maximum stress of stacked cartons is concentrated at the corners of the cartons and the short side of CFC has been found to be more resistant to buckling (Fadiji *et al*., 2019).

Fruit cartons need to withstand compressional, shock and vibrational forces in the handling chain (Pathare & Opara, 2014; Fadiji *et al*., 2016a; Berry *et al*., 2017). While RPC can have carton face ventilation as high as 25%, given the rigidity of plastic, the same is not true for CFC (Vigneault & Goyette, 2002). Mitchell (1992) found that CFC with vent-hole proportion ranging from 5–7%, the mechanical integrity of the carton becomes critically important. Singh *et al*. (2008) reported a linear relationship in reduction in the compressive strength of single wall CFC and total vent area, similar to the observation by Berry *et al*. (2017). Fadiji *et al*. (2016a) found a reduction in buckling load of the cartons between 8–12% on increasing ventilation of the CFC from 2–7%. The thickness of the linerboards used in carton manufacture and the quality of input cellulose fibres also have a bearing on the mechanical integrity of manufactured cartons. Fadiji *et al*. (2018a) found a linear relationship between liner thickness and compression strength of “standard vent” apple cartons.

In addition to the ventilation area, ventilation number, orientation, and shape affect the buckling of CFC. Fadiji *et al*. (2016a) found a linear correlation between vent height and carton buckling load. With regards to shape, rectangular vent-holes better retain carton mechanical strength compared to circular vent-holes (Fadiji *et al*., 2016a). Jinkarn *et al*. (2006) reported that circular vent-holes at carton centre reduced carton mechanical integrity less compared to oblong vent-holes, contrary to Han & Park (2007) that found that circular vents reduce the CFC mechanical strength more compared vertical oblong vents. With regards to position on the carton, vents need to be remote from vertical corners of cartons (Vigneault *et al*., 2009). Therefore, design considerations of new cartons ought to take into consideration the fruit weights, handling conditions (especially temperature and relative humidity) and stacking requirements in designing sturdy cartons that will deliver fruit without mechanical damages like bruises, dents, and cuts, to the ultimate consumer. Table 4.2 lists some additional vent-hole design characteristics on CFC face and their effect on the fruit carton strength.

4.4.2. Space usage/cargo density

Packaging designs are affected by intended market destinations (domestic or international), cooling requirements, fruit properties, package properties, retailer specifications, etc. leading to cartons of different geometrical configurations and size in the fresh fruit industry (Opara & Zou, 2007; Berry *et al*., 2015). Ample space utilisation in the cold rooms and reefers is an important carton design consideration, especially during peak produce season. Space and cargo density is a function of fruit size and how this influences the packaging arrangement, carton size, number of layers in one carton, weight of the carton, and eventually weight of a fully loaded refrigeration container. The size of the fruit will determine the design of the tray and the number of layers of trays within a designed carton (Singh *et al*., 2013; Berry *et al*., 2015).

For cartons with the same base dimensions (footprint), tray designs are made to suit different sizes of fruit through staggering or uniform alignments, for example, tray designs used in the pomegranate industry (Fig. 4.11). Staggered tray design (Fig. 4.11 (a), (c), (d)), uniform alignment (Fig. 4.11 (b)) are all designed in consideration of the fruit diameter and this will eventually influence the carton height and weight. Pomegranate cartons packaged with lower fruit count (6–8) (larger diameter fruit above 80 mm) are 118 mm high, yielding a gross weight over 4.5 kg, while higher counts (10–16) (smaller fruit diameter – 80 mm and below) are packaged in cartons with 104 mm height, gross weight 3.8 kg (Muller, J.C., 2019, General manager, Sonlia Pack-house, Wellington, South Africa, personal communication, 10 May).

Additionally, the number of layers of fruit in one carton is primarily dependent of the fruit weight with heavier fruit packaged in one or two layers while lighter fruit, for example, apples and pears are packaged in up to 4 or more layers within as single carton. (Singh *et al*., 2013; Berry *et al*., 2015, 2016; Fadiji *et al*., 2016, 2017).

Table 4.2 Effect of vent-hole characteristics on corrugated fibreboard carton mechanical strength

Vent-hole characteristic	Main finding(s)	Reference(s)
Vent shape	Ventilation holes with a vertical oblong shape produce smaller stress level, the least surface area of stress concentration, and have the highest structural stability against compression	Han *et al*. (2007)
Vent area	Increase in vent area of CFC beyond 8% does not significantly increase the cooling rate	De Castro *et al*. (2004)
Vent area	There is no reasonable increase in cooling rate with vent area of CFC increase beyond 7%	Delele *et al*. (2013a)
Vent position	To minimise loss in the mechanical strength of cartons, vents should be 40 to 70 mm away from all carton corners	Thompson *et al*. (2008)
Vent area	Cartons with vent area above 5% require careful design to achieve mechanical integrity of CFC	Thompson *et al*. (2002) Mitchell (1992)
Vent area	There is 0.56-1.08% reduction in structural strength following a 1% increase in vent area of corrugated carton	Singh *et al*. (2008)
Vent shape	Rectangular and parallelogram vent-holes have higher compressional strength than circular vent-holes	Singh *et al*. (2008)
Presence/absence	There is 20-50% loss in strength of single wall CFC due to presence of vent and hand holes	Singh *et al*. (2008)
Vent area	Loss in carton strength varies linearly with total vent area	Singh *et al*. (2008)

Most fruit handling is done on standard ISO2 pallet (1.0 × 1.2 m) and thus depending on the carton footprint, the cartons are arranged in different numbers to fill up the base of the pallet (Fig. 4.11). For example, in a study on packaging cartons used in the pomegranate industry, Mukama *et al*. (2017) found two stack configurations where one carton footprint required 10 cartons to fill up the pallet base while the other required 12 cartons. Berry *et al*. (2015) identified four different configurations (5, 7, 8, and 10) for cartons used in the pome industry (Fig. 4.11). A standard 40-ft refrigerated truck takes 20 standard ISO pallets when fully loaded (Defraeye *et al*., 2015). These are loaded to a height of about 2.2 m leaving the top space for airflow circulation (Fig. 4.9). Thus, depending on the carton height and weight of each carton, a fully loaded container will take a particular number of cartons which will further determine the tonnage.

In cold storage, speedy forced air cooling as affected by package vent-hole design and internal packages will determine the turnover of the fruit that gets cooled and thus available space in the cold room especially in peak harvest season. The design of the cartons and how the vent-holes eventually align in a stack of cartons has significant effects on the cooling rates and uniformity of the forced air cooling process and thus overall turnover of the process (Ambaw *et al*., 2017).

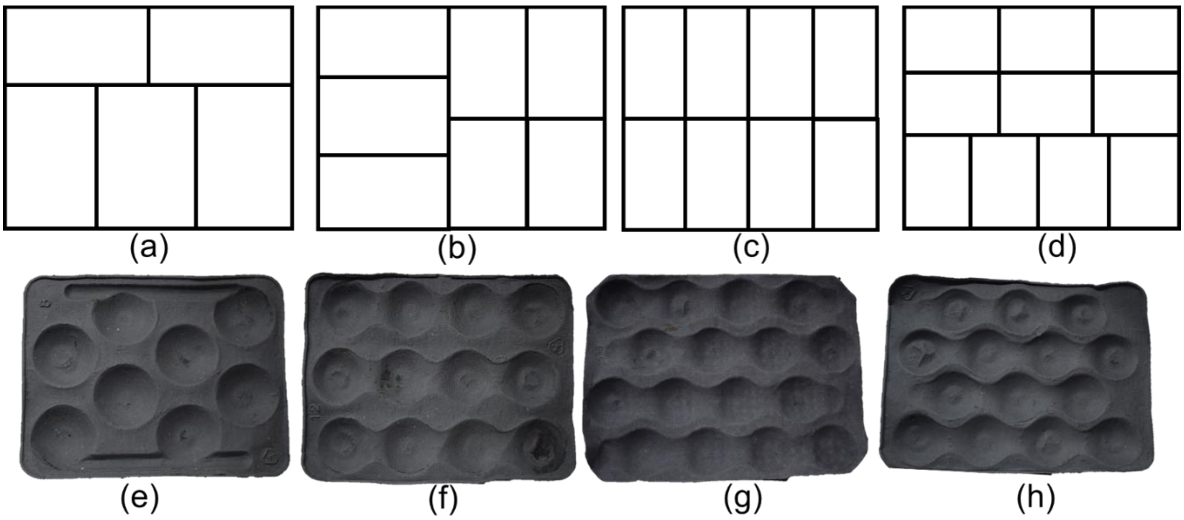

Fig. 4.11 Schematic showing different pallet stacking configurations (top row) of cartons with different footprints used in the apple and pear industry: (a) 5, (b) 7, (c) 8, and (d) 10 (Berry *et al*., 2015), and different trays (bottom row) used in the pomegranate industry in a carton with similar foot print (0.39 × 0.29 m) sorted according to fruit size (e) 8, (f) 12, (g) 16, and (h) 14

4.4.3. Temperature and humidity considerations in fresh fruit CFC packaging

During storage and transportation, corrugated fibreboard cartons are often predisposed to low temperature high humidity environments. Fresh produce are transported and stored under these conditions to preserve quality. This causes moisture uptake by the CFC which has considerable influence on the package strength through weakening of bonds between cellulose fibres (Allaoui *et al*., 2009; Ngcobo *et al*., 2013). This weakening of the bonds could result into gradual loss of mechanical strength due to mechano-sorptive creep—where CFC permanently deform under mechanical load (Berry *et al*., 2019). Fadiji *et al*. (2016a), for example, reported between 11–16% loss in compression strength of apple cartons under low temperatures (0 °C; 90% RH) compared to standard atmospheric conditions (23 °C; 50% RH). Pathare *et al*. (2016), demonstrated a reduction of the maximum carton compressive strength by 618 N per 1% increase in the moisture content of the CFC. The moisture content increased from 5.05% db (g water/g dry matter) to about 11% after 4 days in cold storage and remained almost constant for the rest of the storage days until day 43 (Pathare *et al*., 2016). It is thus paramount to design cartons that will remain strong under specific mechanical loads as a function of fruit weight and stack heights through the long-haul refrigerated transport and refrigerated storage.

Berry *et al*. (2019) developed a CFD model to predict the spatiotemporal moisture distribution within CFC under refrigerated shipping conditions and convective airflow conditions. The developed model could be used to guide refrigerated shipping package design and predict changes in moisture content as well as mechano-sorptive creep (Berry *et al*., 2019). Most of the cartons employed in the fresh fruit industry are produced through a trial and error process instead of a rigorous performance and design evaluation process (Berry *et al*. 2015). This possibly disposes the fruit industry to inefficiency which could be averted through a more holistic package design process that considers the nitty-gritty of the fruit value chain.

4.4.4. Keeping fruit quality

Packages play a key role in preserving the quality of fruit. The most important is the protection of fruit against mechanical damage from compressional forces and external shocks like vibrations during transportation or drops during handling. Mechanical and structural integrity is one of the critical design features for packages for use in the fruit industry (Pathare *et al*., 2012). This is in consideration of the handling chain where cartons have to be stacked onto each other and held in conditions of low temperature high humidity. In addition to mechanical protection, packaging is also applied to minimise loss of produce moisture. For example, in the pomegranate industry, the fruit are packaged in polyliner bags (Fig. 4.12 (a)) that minimise moisture loss from these fruit by creating a moisture saturated environment around the fruit after some time that minimises further loss of moisture from the fruit (O' Sullivan *et al*., 2016; Mukama *et al*., 2019). Polyliner bags also protect packaged fruit from pathogens in the air and modify the levels of O_2/CO_2 in the bag atmosphere meant to further slowdown metabolic processes (Berry *et al*., 2015; Mphalele *et al*., 2016). The limitation with liner packaging is that in case of temperature fluctuations, the moisture could condense on the fruit creating damp conditions that could promote fungal growth and proliferation on fruit surfaces, hence decay (Ngcobo *et al*., 2013).

In keeping fruit quality, packages are designed to enable fast and uniform cooling of fruit (Berry *et al*., 2016, 2017; Getahun, 2017a, b; Mukama *et al*., 2017). This is achieved through proper design of vent-holes on the carton such that cold air easily streams through fruit stacks within a reefer and cold room and during the forced air cooling process (Fig. 4.12 (d)). That way, the deteriorative physiological process of the fruit are slowed down, extending the fruit shelf life and keeping fruit quality. Bruising of fruit caused by the breakage of fruit surface cell membranes due to excessive impact, compression or abrasion of fruit is also one the main mechanical problems in the fruit industry (Hussein *et al*., 2019). Bruised fruit eventually discolour and decay. To minimise this, fruit are packaged in trays (Fig. 4.12 (c)) to minimise their movement during transit (Berry *et al*., 2015; Mukama *et al*., 2017), others are packaged with cushions (bubble pack sheets, sponge sheets, riffled paper) between layers or around individual fruit (Fig. 4.12 (b)) to minimise abrasion against each other during handling and transportation (Chonhenchob & Singh, 2005), and others are sandwiched with foam balls that help absorb mechanical shocks (Jarimopas *et al*., 2008).

Modified and active atmosphere packaging in fresh and minimally processed fruit all aid in extending fresh fruit quality. This is achieved through creation and maintenance of desired atmosphere around the fruit (Jo *et al*., 2014). Since fruit keep respiring after harvest, the main goal in modified and controlled atmosphere packaging is to reduce oxygen conditions to reduce respiration rates, ethylene synthesis, and other oxidative stress processes (Beaudry, 1999; Belay *et al*., 2016, 2017).

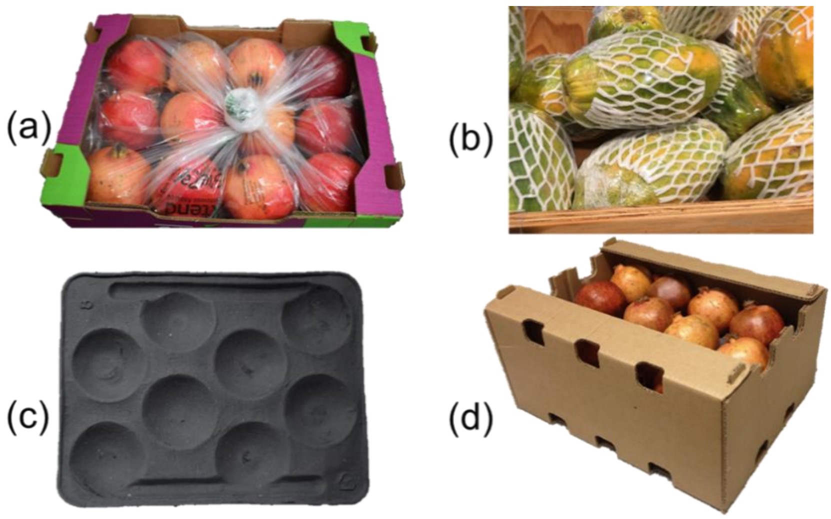

Fig. 4.12 Schematic showing examples packaging with intent to keep fruit quality (a) polyliner bag to modify atmosphere around the fruit and minimise moisture loss (b) foam nets around papaya to minimise fruit abrasion against each other (c) tray meant to limit movement of packaged fruit (d) carton with vent-holes meant to deliver cold air to the fruit within the carton

4.5. Application of mathematical modelling in fruit packaging design and analysis

4.5.1. Aspects of mathematical models in postharvest applications

The complexity of air movement inside stacks of cartons and around individual fruit makes experimental measurements and information of local airflow, heat and mass transfer very difficult, time consuming and challenging. Package design and evaluation should employ a multiparameter approach giving a holistic assessment of all functionalities and parameters to help avoid contradictions in the design requirements. For example, increasing the ventilation area to improve cooling rates without consideration of the carton strength may result in a carton lacking in mechanical integrity, increasing chances of fruit mechanical damage. Mathematical models are important in reducing time and saving costs that would have gone into experimental studies (Delele *et al*., 2010; Ambaw *et al*., 2013a, b; Fadiji *et al*., 2019). The models allow exact control of operating parameters while providing vital information like the airflow, mechanical stress, mechanical strain, and temperature patterns within the stack of fruit under refrigeration conditions; providing mechanisms and performance details of the processes (O'Sullivan *et al*., 2016; Fadiji *et al*., 2018a, b, c).

4.5.2. CFD modelling of postharvest applications

4.5.2.1. Governing equations

Computational fluid dynamics employs mathematical equations that are statements of conservation of mass, momentum, and energy laws (Zhao *et al*., 2016). Airflow and heat transfer in horticultural cooling systems is modelled using the three-dimensional Reynolds-averaged Navier-Stokes equations. These include (Eq. 4.1–4.3):

$$\nabla \cdot \mathbf{U} = 0 \tag{4.1}$$

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot (\mathbf{U} \otimes \mathbf{U}) - \nabla \cdot \left(\left(\frac{\mu + \mu_t}{\rho_a} \right) \nabla \mathbf{U} \right) - S_U + \frac{1}{\rho_a} \nabla p = 0 \tag{4.2}$$

$$\rho_a C_{pa} \left(\frac{\partial T_a}{\partial t} + \mathbf{U} \cdot \nabla T_a \right) - \nabla \cdot \left((k_a + k_t) \nabla T_a \right) - Q = 0 \tag{4.3}$$

where U is the vector of the velocity (m s^{-1}), t is time(s), μ is the dynamic viscosity of air (kg $m^{-1}s^{-1}$), μ_t is the turbulent eddy viscosity (kg $m^{-1}s^{-1}$), p is pressure (Pa) causing the fluid flow and S_U (m s^{-2}) is any momentum source inside the fluid domain. S_U accounts for any momentum source in the flow domain, C_{pa} (J kg^{-1} K^{-1}) is the heat capacity of air, ρ_a (kg m^{-3}) is the density of air, T_a (K) is the air temperature, k_a (W m^{-1} K^{-1}) is the thermal conductivity of air, k_t (W m^{-1} K^{-1}) is the turbulent thermal conductivity.

To model airflow coupled with moisture transport, the basic heat transfer model (Eq. 4.3) incorporates respiration and transpiration of produce and heat gain/loss from evaporation/condensation of water on the produce surface (Eq. 4.4 and Eq. 4.5)

$$(\rho_a C_{pa})\left(\frac{\partial T_a}{\partial t} + \mathbf{U}\cdot\nabla T_a\right) = \nabla\cdot\left((k_a + k_t)\nabla T_a\right) + h_{pa}\left(T_p - T_a\right) \tag{4.4}$$

$$(\rho_p C_{pp})\frac{\partial T_p}{\partial t} = \nabla\cdot\left(k_p \nabla T_p\right) + h_{pa}\left(T_a - T_p\right) + Q_r - Q_v \tag{4.5}$$

where $h_{pa}\left(T_p - T_a\right)$ is the heat exchange across the interface between the produce and the cool store atmosphere, Q_r is respiration heat generation and Q_v is heat loss due to evaporation of water from the surface of the produce. Modelling the moisture distribution requires Eq. (4.6) to be coupled to the basic Navier-Stokes equations.

$$\rho_a \frac{\partial G}{\partial t} + \nabla\cdot\left(G\mathbf{U} - (D_a + D_t)\nabla G\right) = m \tag{4.6}$$

where G is moisture concentration in cold room, D_a is diffusivity of moisture in air, D_t is turbulent diffusion coefficient and m is rate of evaporation of moisture from produce surface.

Wu & Defraeye (2018) incorporated generic models (Eq. 4.7 and Eq. 4.8) into the basic CFD models based on kinetic rate-law (Wu *et al.*, 2018) to model the change in quality of fruit attributes like colour, texture, etc.

$$-\frac{dA}{dt} = \gamma A^n \tag{4.7}$$

where t is the time (s), γ is the rate constant (s^{-1}), n is the order of the reaction. The temperature driven quality changes can be described by an Arrhenius relationship (Eq. 4.8).

$$\gamma(T_p) = \gamma_0 e^{\frac{-E_a}{RT_p}} \tag{4.8}$$

Where γ_0 is a constant (d^{-1}), E_a is the activation energy (J mol^{-1}), R is the ideal gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature (K). The constants γ_0 and E_a can be inferred from quality decay data.

4.5.2.2. Model geometry

The geometry of the horticultural system under CFD analysis needs to be defined. This could be a single fruit to an entire loaded cold store/reefer. These model geometries are created using computer-aided design (CAD) software like ANSYS Design-Modeler, AUTOCAD, Solidworks, etc., or using 3D image data that could be obtained from magnetic resonance imaging (MRI) (Young *et al*., 2012; Ambaw *et al*., 2013a). The complexity of the geometry increases from where a single fruit is considered to fully loaded cold store or reefer. This increases the computation costs and time (Defraeye *et al*., 2015b). Therefore to reduce costs and time, assumptions are made, for example, assuming even temperature distribution across all layers in the stack during precooling, and hence analysing a single layer out of the stack in a cold room (Ambaw *et al*., 2017), taking one row of cartons on a pallet instead of the entire pallet or container (Defraeye *et al*., 2015b). For the purpose of analysing a fully loaded cold storage room or reefer, the porous medium approach that involves a volume-averaged version of the Reynolds Averaged Navier-Stokes equations could be employed. This procedure transforms the cold room/reefer (porous medium) consisting of stacked fruit and air spaces into a continuous and homogeneous medium, characterized by properties such as porosity, tortuosity, and interface transfer coefficients (Ambaw *et al*., 2013b, 2014; Getahun *et al*., 2017a, b).

4.5.2.3. Discretization

This step involves formation of a computational grid from the partitioning of the spatially continuous computational domain into several nonoverlapping subdomains, a process called discretisation (Zhao *et al*., 2016). The grid shapes can be pyramidal, tetrahedral, triangular prism, or hexahedral. The accuracy and reliability of the solution is dependent on the size of the grid. Smaller elements are more accurate, though take a longer time to process and require more memory (Norton & Sun, 2006; Ambaw *et al*., 2013a; Zhao *et al*., 2016). Grids can be structured, where the geometry shape is relatively even and thus the cells connect regularly, unstructured, where the cell elements do not connect regularly or a mixture of the two (hybrid).

Hybrid grids are common in horticultural cold chain CFD models given the complexity of the geometry of packed produce (Delele *et al*., 2013a; Ambaw *et al*., 2014; Defraeye *et al*., 2014; O'Sullivan *et al*., 2016). After meshing, properties of fluids and solids, interface boundary conditions, and initial conditions in the simulation must be specified (Smale *et al*., 2006). The next step is transforming the governing partial differential equations over the mesh. The governing equations are discretised over the mesh and time is discretized for transient problem. (Zhao *et al*., 2016).

4.5.2.4. Simulation techniques

Different numerical techniques are used to discretise the computational domains, the most important include finite elements, finite differences and finite volumes techniques (Ambaw *et al*., 2013a; Zhao *et al*., 2016). Of all the techniques, the finite volume techniques are easily programmed, understandable, have high computation efficiency, and have become the method of choice for CFD numerical studies (Norton & Sun 2006; Delele *et al*., 2013a, b, c; Ambaw *et al*., 2014, 2017; Defraeye *et al*., 2014; Getahun *et al*., 2016, 2017; O'Sullivan *et al*., 2016, 2017). The finite element method has a lower resolving speed and is not widely used in commercial packages, while the finite difference technique is rarely used in engineering fields because it requires extremely fine meshes that are difficult to process (Zhao *et al*., 2016).

The most common commercial software applied in the CFD in the horticultural chain studies is made by ANSYS®. This includes, ANSYS® Design-Modeller™, ANSYS® Meshing™, ANSYS® CFX™ (Ambaw *et al*., 2013b, 2014, 2017; Berry *et al*., 2019), and ANSYS Fluent™ (Defraeye *et al*., 2013, 2015b; Berry *et al*., 2016; 2017; O'Sullivan *et al*., 2016, 2017; Getahun *et al*., 2017a, b). These software have up-to-date physical models including multiphase flow, porous media, laminar and turbulent transition, heat transfer as well as other functional models. The software is also easily compatible with most CAD software (Norton & Sun, 2006).

4.5.2.5. Model validation

CFD models must be validated experimentally to prove their accuracy before making any decisions. Quantitative data, for example, temperature distribution or fluid velocity in the horticultural systems require high accuracy levels, thus comparison with experimental or highly accurate numerical results will help determine the error of the simulation. Temperature history of the fruit thermal centre was measured with T-type thermo-couples to validate numerical results in CFD model on cooling of pomegranate fruit in different carton designs

(Ambaw *et al*., 2017). Getahun *et al*. (2017a, b) measured air velocity in different sampling points, including free region between the two stack rows and between the stacks and roof in a fully loaded refrigerated container with TVS 1100 data logger with candle stick sensors (Fig. 4.13). The velocity was compared with the model captured the velocity profiles giving an average prediction error of 26 ± 2%.

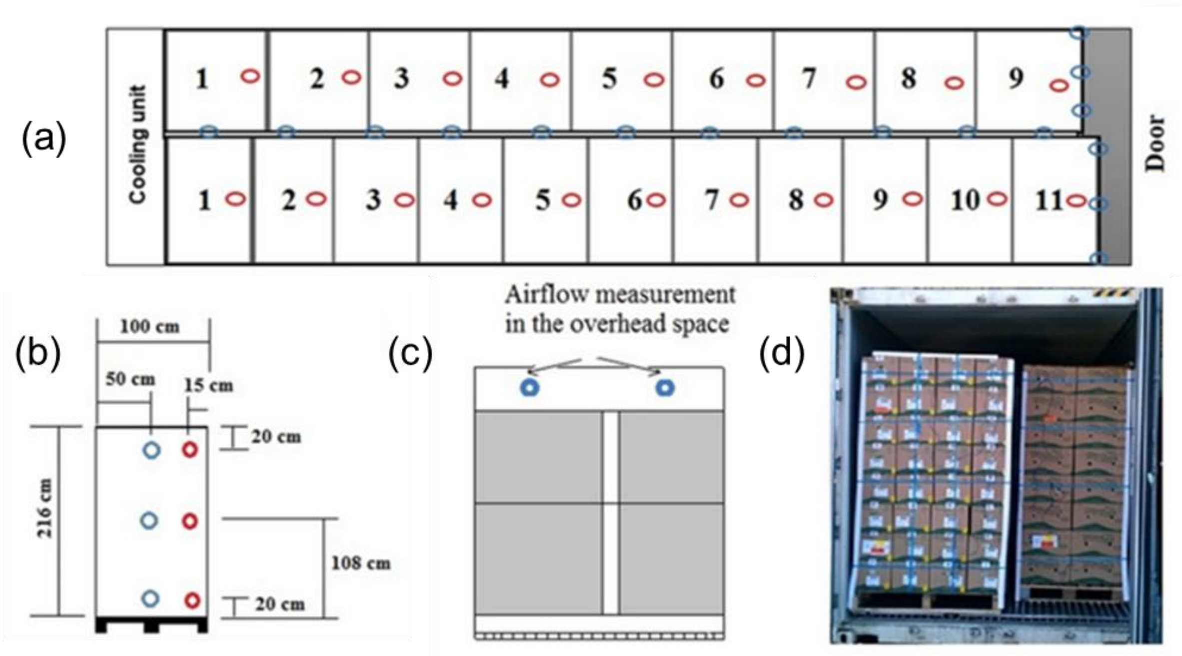

Fig. 4.13 Schematics of the position of pulp temperature sensors (red circle) and air velocity sensors (blue circle) in a fully packed reefer container: (a) top view, (b) side view of a pallet in a row, (c) overhead space, and (d) snapshot of a fully packed reefer with sensors (Getahun et al., 2017a)

4.5.2.6. Notable findings

Recent studies and key findings from different studies that used CFD are summarised in Table 4.3. The studies applied CFD to packaging and cooling systems for various fruits ranging from apples, pomegranates, citrus, straw berries to kiwifruit. These investigated different problems in the fruit cold chain including mass loss in fruit (Han *et al*., 2018), effect of refrigerated container floor design on air circulation (Getahun *et al*., 2018), effect of multiscale packaging on fruit cooling (Berry *et al*., 2016; Ambaw *et al*. 2017), effect of internal packages on fruit cooling, airflow and energy needs of fruit precooling (Berry *et al*., 2016; Ambaw *et al*., 2017; O'Sullivan *et al*., 2017), etc. Accuracy of the findings (numerical vs experimental) varied between 10–25%, including modelling of airflow velocities within stacks of currently used commercial pomegranate fruit packages (Fig. 4.14), cooling and airflow performance of new package designs and modes (Defraeye *et al*., 2013), and optimal airflow velocities (Han *et al*., 2017) (Table 4.3).

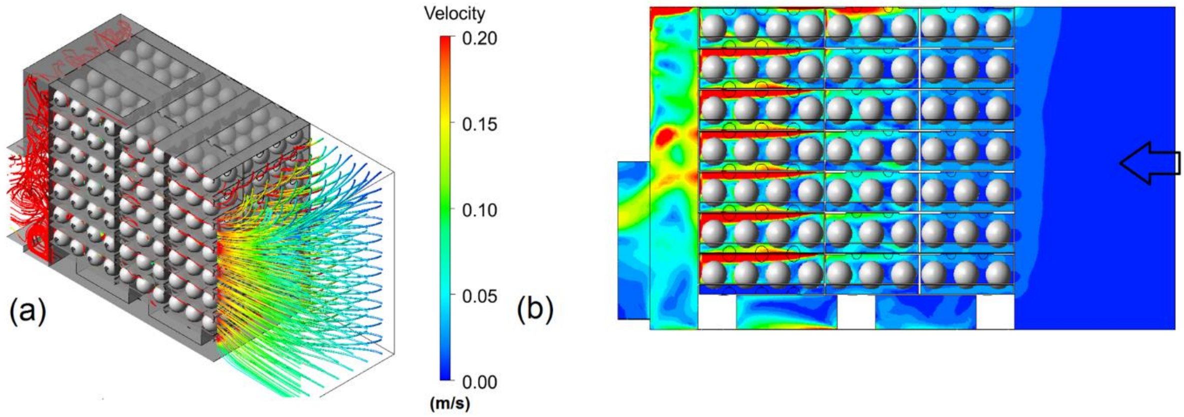

Fig. 4.14 Simulated streamlines of air velocity in stack of fruit (a), and (b) contours of velocity on vertical plane sectioning the fruit stacks (Ambaw *et al*., 2017)

Table 4.3 Examples of recent studies applying computational fluid dynamics (CFD) in analysis of corrugated fibreboard cartons used in the fruit industry

Fruit type	Study	Key findings	Reference
Table grapes	Effect of table grape packaging and stacking on heat and mass transfer	Presence of carry bag increased 7/8 cooling time by 97.3%, non-perforated liners reduced moisture loss but caused condensation in packages, stacking affected airflow, cooling and moisture transfer	Delele *et al*. (2013c)
Citrus	Cooling performance of existing and new corrugated fibreboard cartons for citrus fruit	New container designs showed significant improvement in cooling	Defraeye *et al*. (2013)
Citrus	Cooling of citrus fruit during the long-haul marine transport	Low airflow rates in reefers induced slower fruit cooling and caused heterogeneous cooling, gaps between pallets lead to airflow short circuiting lowering cooling rates	Defraeye *et al*. (2015b)
Citrus	Airflow and heat transfer inside horticultural packaging system using 3-D CFD model	Heterogeneous airflow and temperature distribution; reasonable increase in cooling rate was only recorded for increase in vent area up to 7%	Delele *et al*. (2013a, b)
Apples	Integral approach to evaluate cooling rate, cooling uniformity, energy efficiency and apple fruit quality in different ventilated package designs	Optimal cooling velocity for the studied packaging designs was 0.4–1 m s^{-1}	Han *et al*. (2017)

Table 4.3 *Continued*

Fruit type	**Study**	**Key findings**	**Reference**
Apples	Multiparameter analysis of impact of vent-hole design and internal packages on apple cooling and airflow characteristics	Addition trays to existing commercial design increased ventilated energy consumption by 31%, airflow was better distributed between fruit layers in two new proposed carton designs	Berry *et al*. (2016)
Apples	Effect of vent-hole design on cooling and carton mechanical strength	Multi-vent carton design used 58% less cooling energy and significantly improved cooling uniformity compared to commercial design	Berry *et al*. (2017)
Apples	Evaluate the cooling characteristics, moisture loss, and energy consumption during precooling of palletized apples	Mass loss in fruit is primarily influenced by cooling time rather than airflow rate, reasonable increase in cooling rate and uniformity was obtained with increase in airflow rate up to 2.3 l s^{-1} kg^{-1}	Han *et al*. (2018)
Kiwifruit	Optimal cooling conditions and package design for forced air cooling (FAC) of polylined produce	Package design that channelled air to slowest cooling packages reduced pressure drop and energy requirement of FAC process by 24% and achieved better cooling uniformity	O'Sullivan *et al*. (2017)
-	Absorption of moisture by corrugated fibreboard cartons during shipping	There is relatively low moisture content gradients in fibreboards through the stacked cartons under optimal shipping conditions, heat conduction from outside through the container wall significantly influenced spatial moisture gradients through the cartons	Berry *et al*. (2019)

4.5.3. Finite Element Analysis

A review of the state of the art in the application of FEA in the design of food packaging was done by Fadiji *et al*., (2018c). Finite Element Analysis (FEA) is a powerful numerical technique that is increasingly being applied in the simulation and design of various engineering problems. In the horticultural packaging, FEA is useful in the simulation and study of structural design of cartons and their structural performance under different fruit handling conditions (Biancolini, 2005; Hughes 2012; Fadiji *et al*., 2016, 2018a, b, c; 2019). This technique can be used to predict how cartons react to external physical forces like vibration, heat, fluids, and compression, or even change in vent-hole shape and position on the carton (Fig. 4.15) (Fadiji *et al*., 2019). Experimentally validated FEA numerical results help horticultural package designers to develop packages with improved mechanical integrity and strength necessary to protect fruit against mechanical damage (Hicks *et al*., 2012; Fadiji *et al*., 2018a).

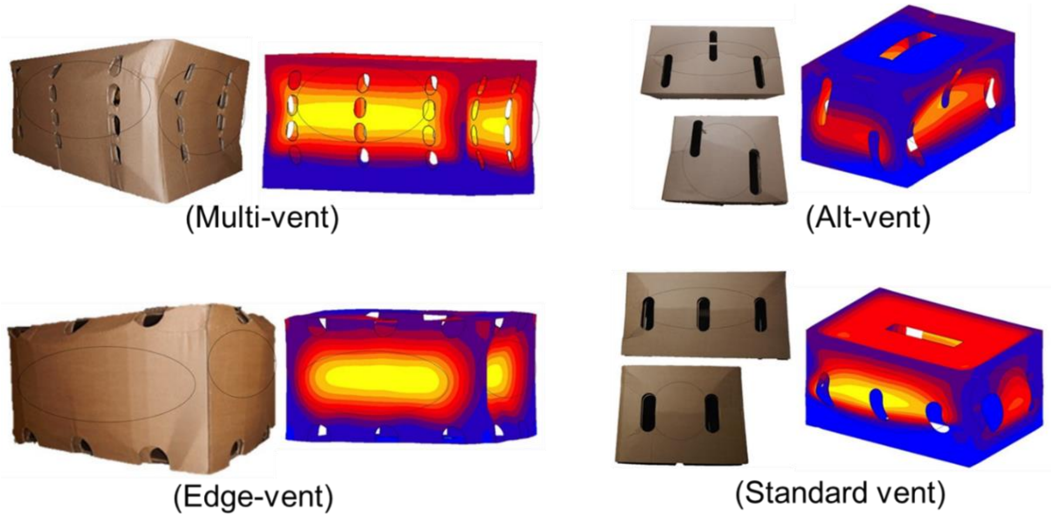

Fig. 4.15 Qualitative visual comparison between experimental and FEA simulation results of the displacement in shape for cartons with 8% vent area for different package vent-hole designs (Fadiji *et al*., 2019)

4.5.3.1. Basic concepts of FEA

FEA analysis basically follows a relatively similar procedure as the CFD where the study structure is created with CAD programs, this is then discretised to several subdomains (finite elements) connected at nodes. Nodes and elements connection is called the mesh. After meshing, the constraints, loads, boundary condition, and the material properties of the structure are defined. Fig. (4.16) gives an example of the FEA simulation steps for a structural modelling process (Fadiji *et al*., 2018c).

4.5.3.2. Governing equations

The FEA process involves piecewise polynomial interpolation at each node of the structure generating a set of simultaneous algebraic equations that are associated with the elements in the mesh (Eq. 4.9). The functions of all the elements are then assembled to form the governing algebraic equation that defines and represents the entire structure (global matrix equation) (Eq. (4.10) (Fadiji *et al*., 2018c).

$$[K]_e\{u\}_e = \{f\}_e \tag{4.9}$$

$$[K]\{u\} = \{f\} \tag{4.10}$$

where, $[K]_e$ is the elementary stiffness matrix, dependent and determined by the geometry, element and material properties, $\{u\}_e$ is the elementary displacement vector which defines the nodes motion under loading, $\{f\}_e$ is the elementary force vector which defines the applied force on the element, $[K]$ is the global stiffness matrix, $\{u\}$ is the vector of the unknown nodal displacements (or temperature in thermal analysis) and $\{f\}$ is the vector of the applied nodal forces (or heat flux in thermal analysis). An account of the commercial software packages used in previous food packaging was discussed by Fadiji *et al*. (2018c), including ANSYS® (Han & Park, 2007; Fadiji *et al*., 2018a, 2019), ABAQUS® (Hammou *et al*., 2012), MS-NASTRAN® (Biancolini & Brutti, 2003; Fadiji *et al*., 2017), and MSC MARC® (Beex & Peerlings, 2009; Fadiji *et al*., 2016a).

4.5.3.3. Model validation

Validation of the FEA results just like in CFD has to be performed experimentally, for example, performing box compression tests (Fadiji *et al*., 2016a, 2019). Fadiji *et al*. (2019) found a good agreement (10%) between the experimental and numerical compression strength results of cartons with different vent area (2%, 4%, and 8%) and corrugated fibreboard grades (B, C, and BC flute boards). The authors reported a negative and almost linear relationship between strength and vent area of the cartons, and that this depended largely on the board grade, with BC-flute being the strongest board. Results were validated experimentally using box compression tester (M500-25CT, Testomatic, Rochdale, United Kingdom).

4.5.3.4. Notable findings

Studies on the use of FEA to study corrugated paperboard cartons can be traced back as early as 1983 when Peterson (1983) studied the stress generated under 3 point loading of corrugated paperboard where they found that the flute part of the corrugated paperboard was the most critical component controlling the applied stress. Fadiji *et al*. (2018a) used an experimentally validated FEA model to study the structural behaviour of corrugated fibreboard cartons with different vent-hole percentages subjected to a compression load. They found that the compression strength of the fibreboard was linearly affected by the fibreboard thickness and ventilation area of the corrugated fibreboard cartons.

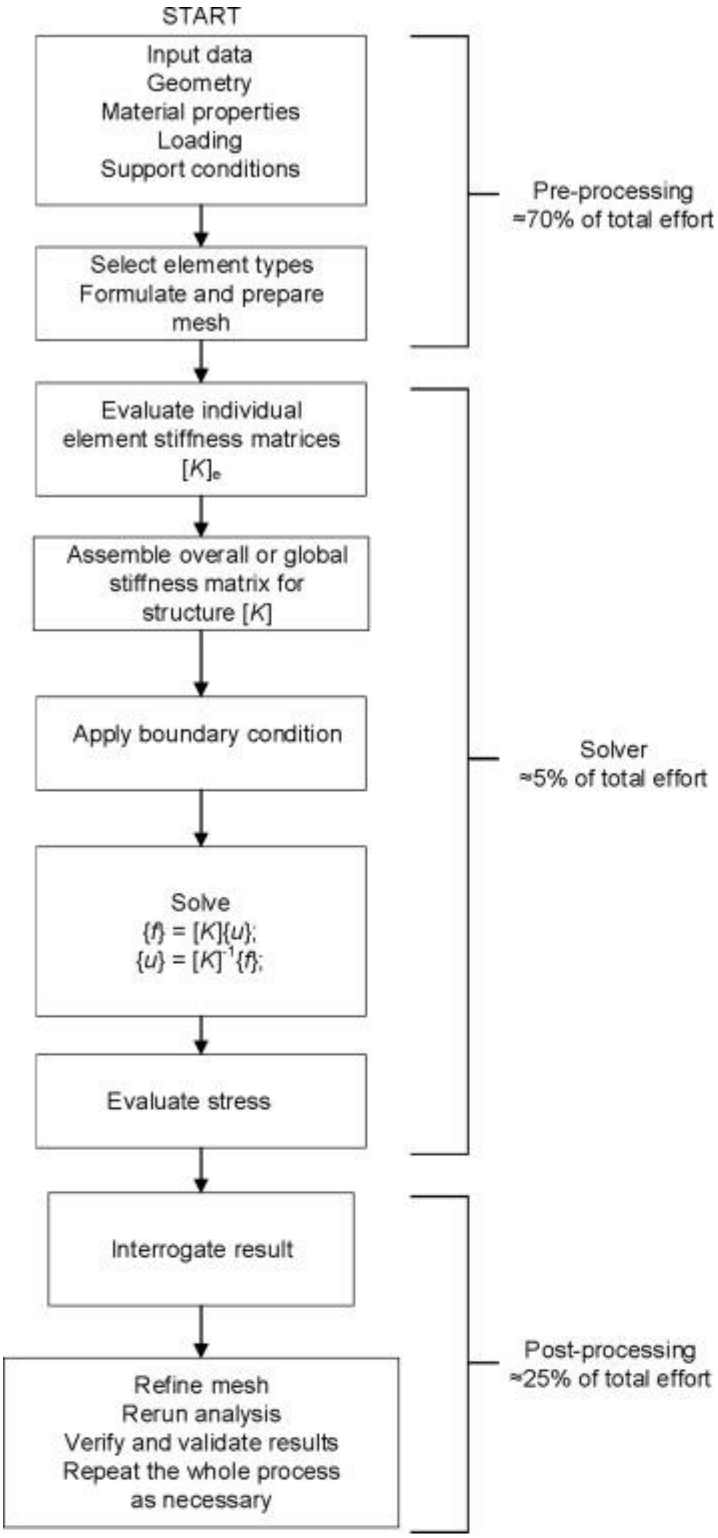

Fig. 4.16 Overview of finite element analysis process-structural simulation (Fadiji *et al*., 2018c)

Other studies (Aboura *et al*. (2004), Hua *et al*., (2017), Zhang *et al*. (2014), Fadiji *et al*., (2016, 2017)) have also successfully applied FEA to study different mechanical aspects of corrugated fibreboard yielding results with accuracy within 10%. Additional studies and their key findings are described in Table 4.4. For all these studies, the simulations results were experimentally validated in order to test the simulated scenarios. However, FEA designers in the field of corrugated packaging have to cope with several inaccuracies due to a number of assumptions and approximations made owing to the complex structure and mechanical behaviour of corrugated paperboard, as well as the complex linearity of paper material (Cheon & Kim, 2015; Fadiji *et al*., 2018c). In more recent simulations, therefore, an equivalent orthotropic plate has been adopted in place of the complex corrugated board (Cheon & Kim, 2015). Combining numerical models like FEA and CFD in corrugated fibreboard studies coupled with experimental validation provides a more integrated investigation of the packaging and cold chain process of the fruit industry geared towards reduction of loses and energy efficiency.

Table 4.4 Examples of recent studies applying finite element analysis in analysis of corrugated fibreboard cartons used in the fruit industry

Study	Key findings	Reference
Buckling of corrugated paperboard carton	Stiffness was low at the top and bottom corners of the package, stiffness was governed by the creases on the package, box compression strength prediction was 7.4% lower than the experimental value for high quality Kraft corrugated paperboard	Biancolini & Brutti (2003)
Modelling folding carton erection failure	The model predicted pattern of deformation of the carton during buckling, model could be used to study the effects of variation in material properties, pack properties and machine settings	Sirkett *et al*. (2007)
Stress levels and distribution on corrugated fibreboard cartons with different vent-hole/hand-hole designs	Appropriate location and pattern of the hand holes were a short distance from the centre to the top of the boxes, vertical oblong-shaped vent-holes symmetrically positioned within a certain extent of distance to the right and left of the centre was most appropriate for vent-holes	Han & Park (2007)
Drop tests of corrugated cardboard packaging containing different foam cushions	Corrugated paperboard package with the corner foam cushions had more damping effect to the shock response of the packed product	Hammou *et al*. (2012)
Model stress and strain distribution on corrugated paperboard boxes made with three types of waveform corrugated fluted medium	Boxes made with V-shaped and U-shaped corrugated fluted medium had good rigidity and good cushioning properties, respectively	Yuan *et al*. (2013)

Table 4.4 *Continued*

Study	Key findings	Reference
Compression strength of the corrugated fibreboard cartons with different vent-hole designs	There was a linear correlation between vent height and buckling load, rectangular vent-holes better retained package strength in comparison to circular vent-holes, vent number, location and shape affected buckling load of corrugated fibreboard cartons	Fadiji *et al*. (2016a)
Apple susceptibility to bruising during simulated transport in ventilated corrugated packaging	Bruise incidence and severity was affected by package design and vibration frequency, top layer fruit were more susceptible to bruising	Fadiji *et al*. (2016b)
Mechanical properties of corrugated fibreboard under different environmental conditions	Modulus of elasticity reduced by 20%–53% at 0 °C; 90% RH compared to 23 °C; 50% RH for all studied paper grammages, modulus of elasticity was higher in the machine direction (MD) than other directions for all the paper grammages	Fadiji *et al*. (2017)
Behaviour of corrugated fibreboard cartons subjected to shocks	Drop height of the packed product was strongly related to the velocity change that products experience in transportation and handling	Luong *et al*. (2017)
Compression strength of different corrugated fibreboard carton designs with different vent-holes designs and fibreboard grades	There was a negative and almost linear relationship between compression strength and vent area, Packages with BC-flute and B-flute board grade had the highest and lowest compression strength, respectively, functionality of package vent-hole design is tied strongly to the properties of the chosen board grade, short side of corrugated fibreboard cartons is more resistant to buckling	Fadiji *et al*. (2019)

4.6. Conclusion

This review discussed the main design considerations for packaging used for fresh fruit in the cold chain. The importance and limitations of vent-holes on cartons were highlighted, requiring a compromise between achievement of fast and efficient cooling and maintenance of mechanical integrity necessary to mechanically protect fruit. Further, the review discusses the benefits and shortcomings of internal packages and highlights the importance of a multiparameter approach that tests packaging for suitability of all processes (airflow, cooling characteristics, strength, effect on fruit quality, effect of internal packages, stacking requirements) in order to develop optimum designs for specific produce in effort to reduce postharvest losses and feed the future. The unique nature of individual fruit and handling conditions makes optimisation of packaging for each fruit paramount to achieve the best postharvest handling programs and ultimately reduce food waste.

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Declaration by the candidate

With regard to Chapter 5, pages 133–150, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
Compiled and edited manuscript in its entirety throughout the publication process	85

The following co-authors have contributed to Chapter 5, pages 133–150:

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Declaration with signature in possession of candidate and supervisor **Signature of candidate**	16/08/2019 **Date**

Declaration by co-authors

The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5, pages 133–150,

2. no other authors contributed to Chapter 5, pages 133–150 besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5, pages 133–150 of this dissertation.

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Chapter 5

Characterisation of ventilated multi-scale packaging used in the pomegranate industry in South Africa

Abstract

Ventilated corrugated packaging are the most widely used packaging in the pomegranate industry. The ventilations aid fruit cooling and poorly ventilated cartons result in non-uniform cooling and a higher cooling energy demand. In this study, we found 10 different corrugated fibreboard carton designs being used in the South African pomegranate industry with different ventilations. The carton designs can generally be classified into 'Processing-fruit' and 'Fresh-line-fruit' cartons. The '104MM' cartons are the mostly used export cartons in the industry accounting for 48.0% of the export volumes and then the '118MM' at 15.73 %. The cartons had varied ventilations along the long (4.60–3.82%), short (0.71–5.33%) and bottom faces (0.74–4.66%), with largely open tops. Internal packages, especially liners and trays are also employed in the industry. The carton designs, and the use of tray/polyliner in the pomegranate fruit packages is largely a decision of the exporter and their individual market requirements.

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5.1. Introduction

The global packaging market value is estimated to reach US$ 1 trillion by 2021 with an annual growth rate of 5–7% until the end of the decade (Smithers, 2019). Much of this growth will be in markets in the developing countries including the Middle East, Africa, and South America (Smithers, 2019). Food packaging accounts for over 35% of this global packaging industry in the developed markets and further growth is projected in the developing world markets with higher population growth (Rundh, 2005). Paper, corrugated board and other paperboard package materials account for 1/3 of the global packaging trade (Rundh, 2005; GADV, 2019; Opara & Mditshwa, 2013). Without packaging, supply of food from the point of production to the consumers, movement of perishables, etc. would be unmanageable (Rundh, 2005). Packaging plays roles in marketing and logistics in addition to its primary role of product protection.

Apart from corrugated paperboard, the fresh produce market also employs other package materials, including punnets, plastic crates, plastic and woven nets, (Opara & Mditshwa, 2013). Packaging used in the fresh fruit industry requires ventilation through which respiration and metabolic heat is removed from the fruit environment in the cold chain process (Berry *et al*., 2015). The design of the vent-holes (area, number, position) have an effect on the carton strength and cooling properties of the fruit therein (Fadiji *et al*., 2016; Berry *et al*., 2017; Mukama *et al*., 2017). For corrugated fibreboard cartons, increase in vent area compromises the carton strength (Fadiji *et al*., 2016) though it may improve fruit cooling rates. The design process of such cartons is thus normally a trade-off between achieving structural integrity and adequate and fast cooling.

The horticultural industry uses millions of paperboard cartons to move produce around the world annually. These hold produce in single or multiple layers, have different vent-hole configurations, and are made from a variety of paper materials with different flute/liner configurations. In addition to the cartons, fresh fruit are packaged in internal packages like polyethylene liners, foam nets, trays and punnets (O'Sullivan *et al*., 2016; Ambaw *et al*., 2017). These serve different functions that may include reduction of moisture loss, protection of fruit against abrasion, modification of atmosphere around the fruit, etc. However, some internal packages negatively affect fruit cooling rates, for example, polyliners (Ambaw *et al*., 2017; Mukama *et al*., 2017).

Pomegranate fruit cultivation and demand is on the rise world over given the health promoting benefits associated with the fruit consumption (Rahmani *et al*., 2017). Thus far, consumption of the fruit has been linked to anti-hypertensive, anti-mutagenic and anti-cancer benefits that trace back to phytochemical, antioxidant and radical scavenging properties of pomegranate fruit components (Fawole & Opara, 2012; Opara *et al*., 2016). Pomegranate trees are native to the area between Iran and northern India; however, the trees are now cultivated widely: in Mediterranean basin, the drier parts of Southeast Asia, Malaya, and tropical Africa. The total world production is currently estimated at 3 million tons per year (Erkan & Dogan, 2018). According to Pomegranate Industry overview (2018) by HORTGRO (South Africa), the total area planted by pomegranates increased by 13% from 826 ha in 2017 to 932 ha in 2018. The report projected 1.4 million 4.3 kg equivalent cartons of fruit pack out by 2023 (POMASA, 2019). Total exports have been increasing since 2012 but dropped by 19% between 2017 and 2018 probably due to drought in the Western Cape, the main growing region in South Africa. Most South African pomegranate fruit export is destined to the European market (PPECB, 2019). Europe is a net importer of fresh pomegranates, their total import volume increased from 67,000 tons in 2013 to 95,000 tons in 2017 (CBI, 2019).

There is a growing trend in the use of pomegranates as an ingredient in food, cosmetic, and pharmaceutical industries given their bright red colour, sweet-sour flavour and nutraceutical properties (Fawole & Opara, 2014). However, pomegranates are vulnerable to moisture loss, fungal infections, bruising and decay if the fruit is not properly handled, packaged, and stored after harvest (Kader, 2006; Caleb *et al*., 2012; Munhuweyi *et al*., 2016). Pomegranate shelf life can be prolonged up to 4 months if fruit is kept at temperature and relative humidity (RH), 4–8 °C and 90–95%, respectively. Rapid loss of moisture and the associated shrivelling are the most common challenges after harvest (Fawole & Opara, 2013; Arendse *et al*., 2014). Most tree fruits lose moisture at considerably high rates until attainment of storage temperature. Packaging, cooling, and humidification could greatly avert this loss (Delele *et al*., 2009; Montero-Calderon & Cerdas-Araya, 2012).

Cartons used in the fresh fruit industry are of different designs majorly decided by the exporters, importers, and the consumers (Opara & Zou, 2007; Pathare & Opara, 2014; Berry *et al*., 2015). Berry *et al*. (2015) did a survey of the ventilated fibreboard cartons used in the apple and pear industry in South Africa and found 11 different export cartons that were divided into two major designs: the ‘telescopic’ and ‘display’ cartons. These had different vent-hole designs and the packaging procedure made use of different internal packages: thrift bags, punnets, trays, and polyliner bags. However, there is a dearth of knowledge on the packaging designs currently used in the pomegranate industry which would guide future package designs to meet the demands of the global competitive market. Therefore, the objective of this study was to survey and characterise the packages used in the pomegranate industry in terms of geometric configuration, ventilation and internal packages.

5.2. Materials and methods

5.2.1. Carton survey

A survey of the current packaging used in the pomegranate industry was done between February and June 2019 in two major pack-houses in Wellington, Western Cape, South Africa and in the fresh produce section in the major supermarkets within the Western Cape Province. This province is South Africa's major pomegranate growing area accounting for > 60% of the total annual production (POMASA, 2019). Each of the packages were assessed for:

1) Geometry (length, width, height)
2) Ventilation area
3) Presence of internal packages (trays, polyliner bag)

Up to 3 cartons of each design were assessed to obtain the dimensions and ventilation area.

5.2.2. Pomegranate cartons trade data analysis

Pomegranate fruit export data in the different cartons used in South Africa was obtained from Perishable Products Export Control Board (PPECB, 2019). Each package design had a local 'Pack code' linked to the 'Global Trade Item Number' of fruit exports. Similar to findings by Berry *et al*. (2015) on pome packages, different pack codes were used to describe similar ventilated package designs from different manufacturers and fruit exporters. The number in the 'Pack code' is meant to represent the weight of fruit in the carton (Muller, J.C., 2019, General Manager, Sonlia Pack house, Wellington, South Africa, personal communication, 20 July). However, this is not consistent, for example, 76 kg of fruit is unrealistic for carton 'OPEN TOP - 82 MM' with 'Pack code' D76N just like D82N, and D64A (Table 5.1).

5.3. Results and discussion

5.3.1. Pomegranate trade statistics

All packages used in the South African pomegranate fruit export between 2015 and 2018 are shown in Table 5.1 (PPECB, 2019). The ambiguity in the 'Pack names' is clearly visible.

Standardisation of the 'Pack names' is necessary to reduce confusion in future. The majorly used export cartons characteristics (geometry, loading, ventilation) and their suggested 'Pack names' are described in Table 5.2. The '104MM' cartons are the mostly used export cartons in the industry accounting for 48.00% of the export volumes, followed by unnamed cartons at 22.27%, the '118MM' at 15.73 %, '170MM' cartons at 7.67%, the '82MM' cartons at 3.53% and then the '190MM' cartons at 1.69% (Table 5.1 and Table 5.2). However, the volume of the '82MM' cartons exported in 2018 dropped sharply from 48, 955 cartons in 2017 to only 260 cartons in 2018. This is because this carton takes smaller diameter fruit in counts 18 and 20 which are slowly being phased out of the export market (Muller, J.C., 2019, General Manager, Sonlia Pack house, Wellington, South Africa, personal communication, 20 July). Additionally, data for the '105MM' cartons that are used to export a significant amount of fruit (Muller, J.C., 2019, General Manager, Sonlia Pack house, Wellington, South Africa, personal communication, 20 July) could not be traced in the statistics using the 'Pack code' or 'Pack name'. These could be among the 'NULL/NOT AVAILABLE' group of cartons in Table 5.1.

5.3.2. Carton designs

The survey found 10 different carton designs in use in the pomegranate fruit industry. These were manufactured by different companies in South Africa. The different cartons can be grouped into two major carton types: the cartons that are used to package 'Fresh-line-fruit', and cartons used to package 'Processing-fruit'. The dimensions, ventilation, and loading of these cartons are shown in Table 5.2. 'Processing-fruit' is fruit meant for industrial processes like juicing, aril extraction, and extraction of other pomegranate products, while 'Fresh-line-fruit' are sold individually or on weight basis to retailers. The 'Fresh-line-fruit' cartons hold fruit in single layers while in the 'Processing-fruit' cartons, the fruit are jumble packed or place packed.

In the 'Fresh-line-fruit' cartons, there were four main groups of cartons, the '82MM', the '104MM', '105MM', and the '118MM' cartons. The '82MM' carton is used for smaller diameter (< 60 mm) fruit packaged in counts 18 and 20, gross weight 3.5–4.5 kg, fruit in 105MM and 104MM cartons is packaged in counts 10, 12, 14, and 16, gross weight 3.0–4.5 kg (diameter (> 60 < 100) mm), while the '118MM' cartons that hold larger fruit with diameter (> 100 mm) in counts 6 to 8, gross weight 4.3–5.5 kg. The '104MM' and '118MM' cartons have variations including the 'Bini', 'Agri-lock-A', and 'Agri-lock-B' cartons, mainly differentiated by their ventilation and make of the carton tops (Fig. 5.1). The 'Agri-lock-A' and

'Agri-lock-B' cartons (Fig. 5.1) have similar design with top flaps locked in carton material overlaps on the top of the carton, however, the 'Agri-lock-B' cartons have different bottom and top ventilation configurations with semi-circular vent-holes that are continuations of the ventilation along the long side of the carton in addition to the vent-holes at the bottom. This ventilation configuration is achieved by placing oblong vent-holes along the folding line of these cartons. The 'Bini' cartons have the top flap glued on the long side of the cartons (Fig. 5.1).

The International Fibreboard Class Code (IFCC) document is the internationally applied system in corrugated and solid board design that assigns codes and numbers to most common box types to facilitate communication between manufacturers and customers (FEFCO & ESBO, 2007). Under this categorisation, the cartons used in the pomegranate industry are within descriptions: 0432-M, and 0436-M, category: 04 – Folder-type boxes and trays (trays with one piece of board hinged to form side walls and cover with locking tabs). Berry *et al*. (2015) found codes 0773-M, 0200-MA and 4032-M, under which were over 11 different corrugated fibreboard carton designs used for commercial handling of apples and pears. The pomegranate cartons largely had open tops with small fold over flaps.

Table 5.1 Cartons of pomegranate fruit exported from South Africa between 2015 and 2018 by carton type (PPECB, 2019)

Pack name	Pack code	2015	2016	2017	2018	Total	%
DOUBLE 4.75KG INTR 400X300X104	D04I	388501	581421	545143	466389	1981454	43.26
NULL	NA	170944	259102	387351	174043	991440	21.65
DISPLAY 64 170MM	E15D	80612	39642	77122	133719	331095	7.23
MULTIPLE 4.75KG INTR 400X300X118	M04I	74986	110836	75005	60521	321348	7.02
4.5KG INTR 120 Extra Large Carton	B04I	116258	133260	60680	5400	315598	6.89
4.5KG CARTON 400X300X82	C04I	42334	65452	48955	260	157001	3.43
4.0KG SUPERVENT CARTON	B04S	0	0	10080	132710	142790	3.12
4.0KG DISPLAY 216	D04D	0	16983	46180	10960	74123	1.62
F14D	F14D	38605	13260	14814	6426	73105	1.60
MULTIPLE 5.25KG INTR CARTON	M05I	14378	15580	16994	7740	54692	1.19
MULTIPLE 5.25KG DISPLAY	M05D	0	7577	17550	3612	28739	0.63
NOT AVAILABLE	NULL	1010	11951	8211	7160	28332	0.62
6.09KG CARTON	C15A	25365	0	0	0	25365	0.55
E14D	E14D	0	0	0	19269	19269	0.42
4.00 DISPLAY 228	C04D	0	3120	5860	0	8980	0.20
DOUBLE 5.25 INTR	D05I	3710	0	4760	200	8670	0.19
Display 15 KG	F15D	397	2088	5033	137	7655	0.09
OPEN TOP - 82 MM	D76N	1820	2460	0	0	4280	0.09
DOUBLE 5.25 KG DISPLAY CARTON	D05D	0	2600	170	154	2924	0.06
5KG COMPOSITE 150MM CARTON	B05C	0	1260	0	0	1260	0.03
4.00 COMP 110MM	A04C	0	840	0	0	840	0.02
E12D	E12D	195	130	0	0	325	0.01
OPEN TOP -76 MM	D82N	250	0	0	0	250	0.01
TELESCOPIC 170MM	E15C	100	150	0	0	250	0.01
DOUBLE 5.25KG COMPOSITE CARTON	D05C	200	0	0	0	200	0.00
15KG CARTON	C15, AI5C	95	0	0	1	96	0.00
DISPLAY 10KG	E10D	0	90	0	0	90	0.00
DISPLAY 64 122MM	D64A	0	0	0	3	3	0.00
Total		**959760**	**1267802**	**1323908**	**1028704**	**4580174**	**100**

Table 5.2 General carton design characteristics of cartons used in the South African pomegranate industry

		Fresh-line-fruit cartons								**Packaging-fruit cartons**	
Carton name		**82MM**	**105MM**	**104MM**			**118MM**			**170MM**	**190MM**
Pack code		C04I, D76N, D82N	D03I	D04I, D04D, B04S			M05D, M05I, M04I, B04I			E15D, E15C, E10D, E12D, E14D	F14D, F15D
Carton make				Bini	Agri-lock-A	Agri-lock-B	Bini	Agri-lock-A	Agri-lock-B		
International fibreboard class code		0436-M	0436-M	0436-M	0432-M	0432-M	0436-M	0432-M	0432-M	0436-M	0436-M
Dimensions (mm)	Length	395	325	395	395	395	395	395	395	600	490
	Breadth	295	295	295	295	295	295	295	295	390	390
	Height	82	105	104	104	104	118	118	118	170	190
Long carton side (mm^2)	Total area	32390	34125	41080	41080	41080	46610	46610	46610	102000	93100
	Vent area	1490	3481	4780	3733	3733	4780	3733	3733	14100	11610
	Vent area (%)	4.60	10.20	11.64	9.09	9.09	10.25	8.01	8.01	13.82	12.47
Short carton side (mm^2)	Total area	24190	30975	30680	30680	30680	34810	34810	34810	66300	74100
	Vent area	700	1651	900	707	1410	900	707	1410	1050	525
	Vent area (%)	2.89*	5.33*	2.93*	2.30	4.60	2.59*	2.03	4.05	1.58	0.71
Bottom side (mm^2)	Total area	116525	95875	116525	116525	116525	116525	116525	116525	234000	191100
	Vent area	2945	3662	5345	3507	5427	5345	3507	5427	6750	1414
	Vent area (%)	2.53	3.82	4.59	3.01	4.66	4.59	3.01	4.66	2.88	0.74
Internal packages		Tray & polyliner	Polyliner	Tray & polyliner	Tray & polyliner	Tray & polyliner	Tray & polyliner	Tray & polyliner	Tray & polyliner	Polyliner	Polyliner
Fruit count per carton		18, 20	10, 12, 14, 16	10, 12, 14, 16	10, 12, 14, 16	10, 12, 14, 16	6, 8	6, 8	6, 8	Jumble/place pack	Jumble/place pack
Weight of fruit packed carton		3.5–4.5	3.0–3.8	3.5–4.5	3.5–4.5	3.5–4.5	4.3–5.5	4.3–5.5	4.3–5.5	14–15	14–15
Cartons per pallet layer		10	12	10	10	10	10	10	10	5	6

*Vents act as interlocking spaces and are thus blocked by subsequent carton in stack

5.3.3. Ventilation characteristics

The studied cartons had different ventilation areas (Table 5.2), varying between 4.60–13.82% on the long carton face/side, 0.71–5.33% on the short face, and 0.74–4.66% on the bottom face. However, for the '105MM', '82MM' and '104MM-Bini', and '118MM-Bini' cartons, the vents on the short side are used for locking purposes on stacking and are thus not useful as air passages in the cooling process. Most of the cartons had the recommended 5–7% carton face ventilation to enable compromise between efficient fruit cooling and carton mechanical integrity (Mitchel, 1992; Thompson *et al*., 2008; Delele *et al*., 2013), but, only on the long side. The short side of the cartons largely had ventilation below 5% and so did the bottom faces of the cartons. The 'Bini' cartons had higher bottom ventilation area compared to their 'Agri-lock' counter parts. Thus, these cartons would perform better in facilitating vertical airflow in refrigerated containers (Getahun *et al*., 2017).

The shapes of the vent-holes on the studied cartons were largely semi-circular or oblong along the length and breadth of the cartons (Fig. 5.1) and circular at the bottom. While Jinkarn *et al*. (2006) reported that oblong vent-holes on the vertical carton faces reduced carton mechanical integrity more compared circular vent-holes, Han & Park (2007) found that circular vents reduce the CFC mechanical strength more compared vertical oblong vents. The 'Processing-fruit' cartons largely have large rectangular open areas along the long side of the cartons with very poor or no ventilation along the short side of the cartons. Therefore, stack orientation that predisposes the short side as the airflow inlets for this carton would result into large pressure drops and inefficient fruit cooling rates (Ambaw *et al*., 2017). The '190MM' carton had the poorest bottom (0.74%) and short side (0.71%) ventilation areas.

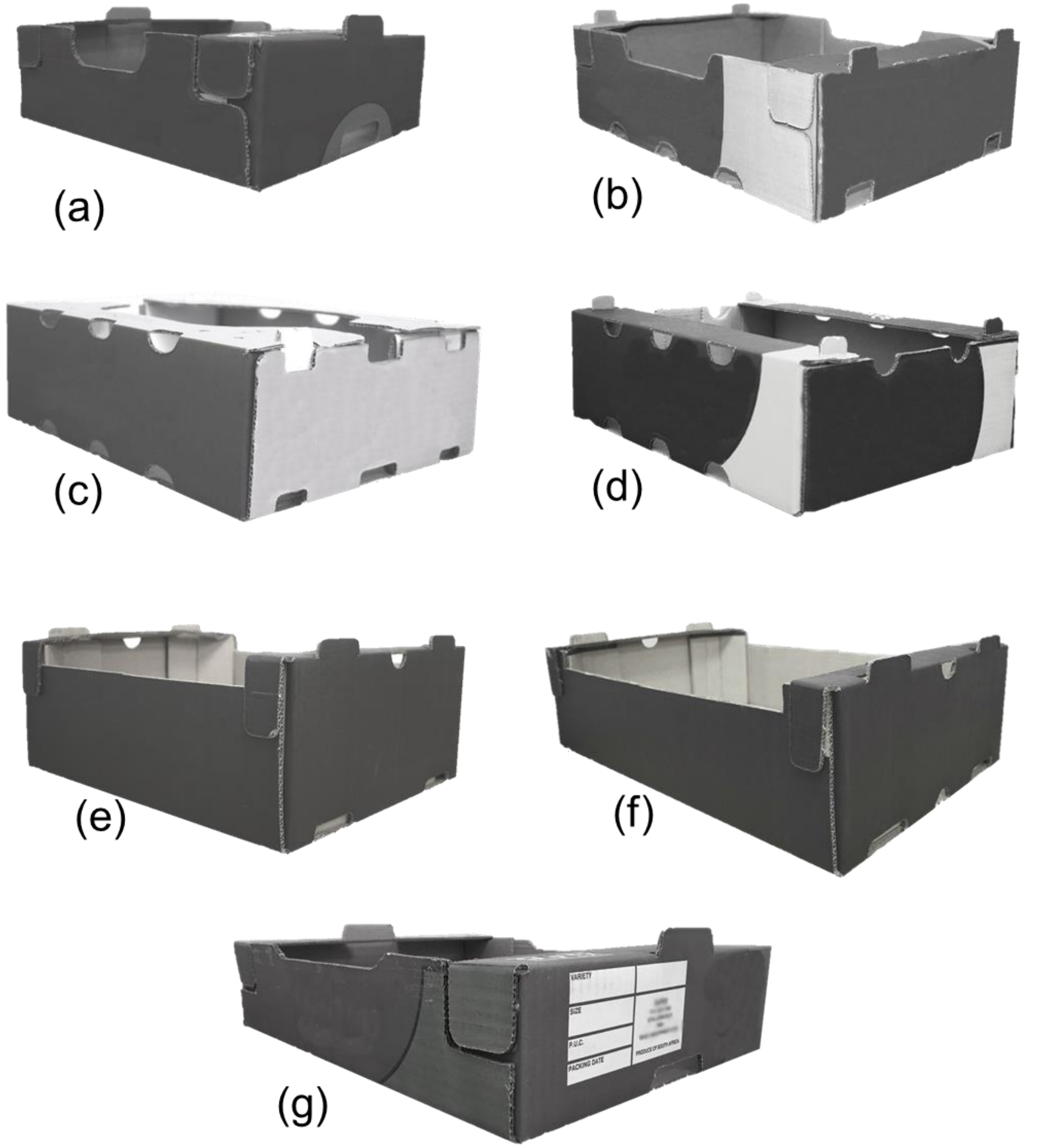

Fig. 5.1 Schematics showing the majorly used cartons in the South African pomegranate industry: (a) '105MM', (b) '104MM/118MM-Bini', (c) '104MM/118MM-Agri-lock-B', (d) '104MM/118MM-Agri-lock-A', (e) '190MM', (f) '170MM', and (g) '82MM'

5.3.4. Internal packages

The use of successive layers of packaging including internal packages is termed multi-scale packaging (Ngcobo *et al.*, 2013; Berry *et al.*, 2015). All the studied cartons are packaged with/without polyethylene liners (polyliner) (Fig. 5.2). The polyliners are employed to minimise moisture loss from the fruit and to modify the environment around the fruit (18–19% O2; 1 % CO2; 98% relative humidity—RH). The use or no use of polyliner is determined by the exporter and market destination. Given that the fruit is waxed with carnauba wax, some exporters of the waxed fruit package their produce without polyliners (Muller, J.C., 2019, General Manager, Sonlia Pack house, Wellington, South Africa, personal communication, 10 May). This is probably because polyliners delay fruit cooling (Ambaw *et al*., 2017; Mukama *et al*., 2017).

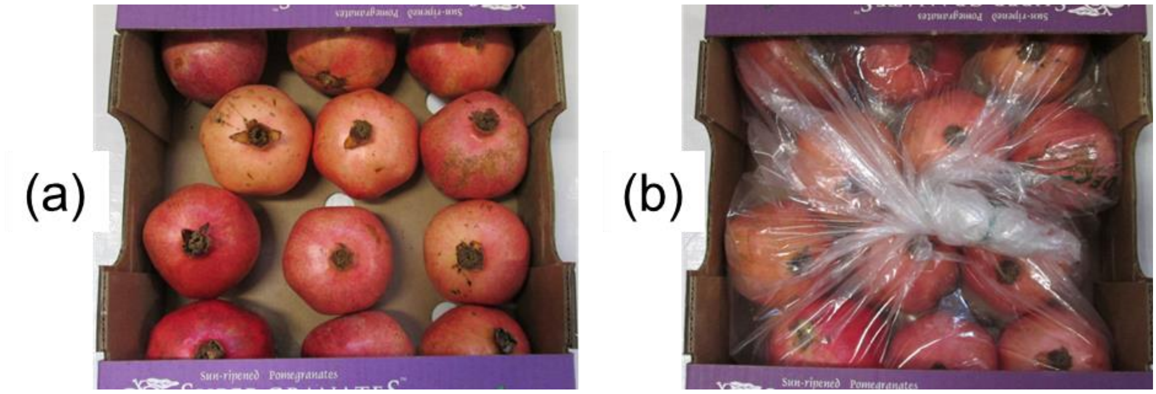

Fig. 5.2 Schematic showing pomegranate fruit packaging without (a) and with polyliner (b)

Trays, made from pulp paper (Fig. 5.3) were used in all the 'Fresh-line-fruit' cartons, except the '105MM' carton that uses no trays. Trays are not also used in the 'Processing-fruit' cartons. Fruit in these cartons were simply jumble or place packed without or within a polyliner. In the '105MM' fruit are placed in the carton with/without polyliner in a single layer without tray. For cases where the polyliners were used, the bags surrounded both the tray and fruit and were tied off at the top with rubber bands. The trays used in the industry exhibited staggered and straight fruit arrangements designed to accommodate different fruit numbers (fruit counts) according to fruit diameter (Fig. 5.3). Given the tray and carton designs, there was blockage of lower vents (100%) along the short and long sides of the carton by the trays (Fig. 5.4).

Studies have shown the effect of internal packages on pomegranate fruit cooling and quality, for example, in a study by Mphalele *et al*. (2016), commercially ripe pomegranate fruit packaged in ventilated cartons with polyliner (passive modified atmosphere packaging) lost significantly lower amount of water in comparison to non polyliner packaged fruit. A similar observation was made by Mukama *et al*. (2019) in a study on moisture loss during forced air precooling of pomegranate fruit in polyliner and no polyliner. However, Mukama *et al*. (2017) and Ambaw *et al*. (2017) found that polyliners increase the energy demand of the forced air cooling process of pomegranate fruit, using up to 3-fold more energy compared to stacks with no polyliners, and increase the pressure drop of the system as well as cooling time by > 6 hours compared to no liner packaging. Internal packages are also used in packaging other horticultural produce, for example grapes (Ngcobo *et al*., 2013), apples, pears (Berry *et al*., 2015), kiwifruit (O'Sullivan *et al*., 2016), etc.

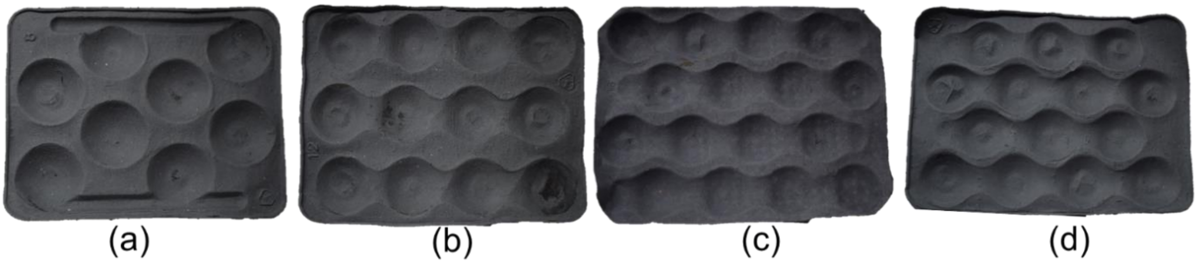

Fig. 5.3 Schematic showing some of the trays used in the pomegranate industry in South Africa: (a) count-8 fruit tray, (b) count-12, (c) count-16, and (d) count-14

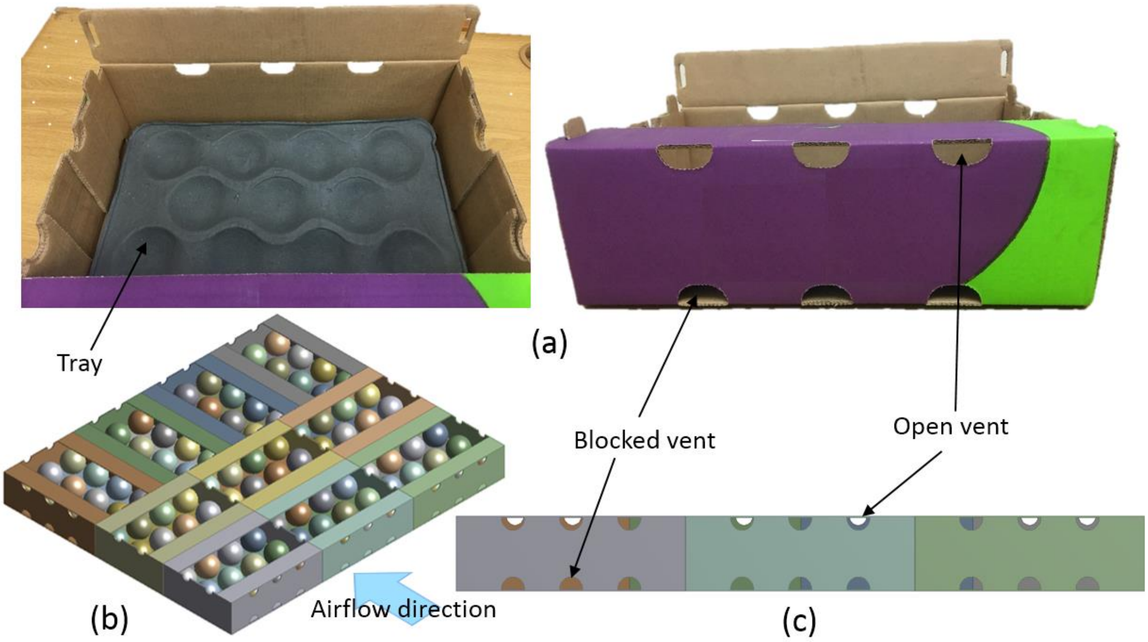

Fig. 5.4 Schematic showing blockage of lower vents along the short and long sides of the carton by the trays: (a) photographic view of inside and the lateral of one carton, (b) top view of carton stack (c) lateral view of carton stack

5.3.5. Stacking configurations

The stacking configurations of the pomegranate fruit cartons on a standard ISO2 pallet (1.0 x 1.2 m) are shown in (Fig. 5.5). Four stack configurations were found in this survey: 5, 6, 10, and 12. The '105MM' cartons are stacked into 12 cartons, the '82MM', '104MM', and the '118MM' cartons are stacked in 10, the '170MM' cartons in 5, and the '190MM' cartons are stacked in 6 cartons on the pallet per layer (Fig. 5.5). Berry *et al*. (2015) found stack configurations 5, 7, and 10 on a standard ISO2 pallet for cartons used in the apple and pear industry. Poor vent-hole alignment (over 50% and greater vent-hole misalignment (blockage)

(Fig. 5.4 (b) and (c)) was observed in the stacking configurations of the '82MM', '104MM', '170MM', and the '118MM' cartons using the 1.2 m side as the airflow inlet due to change of orientation along one line of the cartons on a standard pallet (Fig. 5.5 (a) and (d)).

The orientation of the pallet stack in relation to airflow (1.0 m or 1.2 m) may affect the overall cooling efficiency especially in stacks where the vent-holes along the short carton face have been blocked by interlocking action on stacking (Mukama *et al*. 2017) (Table 5.2). Vent-hole alignment on stacking is very important to prevent obstruction of airflow during cooling which creates high temperature zones within the stack of cartons, with negative implications on the energy requirements of the cooling process and fruit quality (Ambaw *et al*., 2017). It is thus necessary that both the long and short carton faces are ventilated, and that vent-holes align especially for stacking configurations where the cartons orientation may change (Fig. 5.5 (a) and 5.5 (d)).

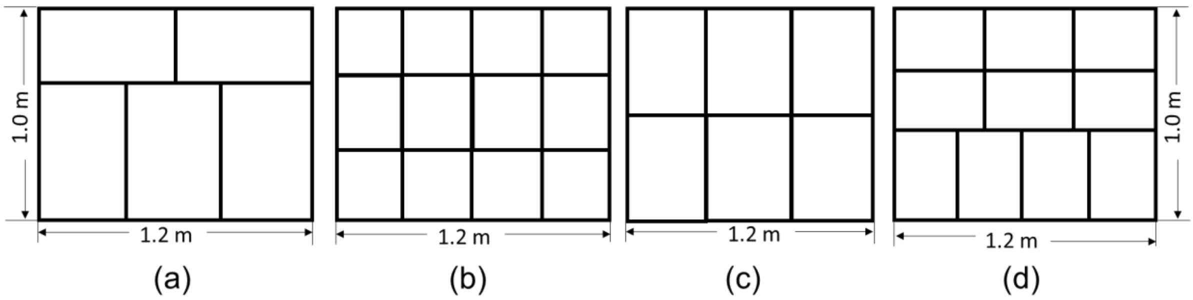

Fig. 5.5 Schematic showing different pallet stacking configurations of cartons used in the South African pomegranate industry: (a) 5, (b) 12, (c) 6, and (d) 10

5.3.6. Retail display

Under retail display, pomegranate fruit were found to be bulked out with other fruit on shelves under ambient condition (Fig. 5.6) where they were sold individually or on weight basis. This type of marketing could possibly have negative effects on the fruit quality. Mukama *et al*. (2019) monitored quality of pomegranate fruit stored under ambient conditions (20 ± 0.36 °C 65 ± 6.79 %RH) over a 30-day period. The authors reported excessive weight loss (up to 29.1% on day 30) which led to shrivelling, deformed appearance and considerably reduced overall fruit visual quality, with signs of shrivel beginning to appear on storage day 6. Display of fruit at 20 °C, 95%RH keeps pomegranate fruit quality for 30 days and beyond. Therefore, pomegranates should preferably be displayed in low temperature environments 5–7 °C (Arendese *et al*., 2014) or high relative humidity environments (90–95%) (Mukama *et al*., 2019) or both.

Fig. 5.6 Pomegranate fruit display in a supermarket in Western Cape, South Africa

5.4. General discussion and conclusion

Efficient fresh produce distribution and marketing requires well designed and efficient packaging and cold storage systems. The survey of ventilated packaging used in the pomegranate industry in South Africa found 10 different corrugated fibreboard carton designs predominantly used in the commercial handling of the fruit. In the apple and pear industry, Berry *et al*. (2015) foud 11 different ventilated corrugated fibreboard designs that were either 'Telescopic' or 'Display'. The designs found in this study were all open top (Display) and could be largely divided into 'Fresh-line-fruit' and 'Processing-fruit' cartons, depending on the end-use of the fruit packaged in the cartons. The carton ventilation areas varied between 4.60% to 13.82% on the long carton face, 0.71% to 5.33% on the short face, and 0.74 to 4.66% on the bottom face. The cartons were largely poorly ventilated on the short faces that leads to poor carton vent-hole alignment and vent-hole blockage in stacking configurations that involve change of carton orientation (long side/short short) on the pallet. Additionally, some cartons were found to have poor bottom ventilation area which has negative effects on vertical airflow in the refrigerated container. Similar variation in ventilation area was found for the apple and pear cartons (Berry *et al*., 2015), varying between 1.92–8.81%, with some cartons like the 'Econo-D' having poor ventilation on both the long (1.09%) and short sides (1.92%).

While only trays and liners are used in pomegranate fruit internal packaging, the apple and pear industry makes use of trays, liners, thrift bags, and punnets. The trays and liners in this study largely block the bottom vent-holes, and trays block the lower vent-holes along the vertical faces (long and short sides) of the cartons in which they are used further worsening the cold chain efficiency. The practical implications of the varied carton design characteristics in the pomegranate packaging have been shown to have a negative impact on the cooling efficiency (Mukama *et al*. 2017). Going forward, with technologies like fruit coating, use of additional internal packages like liners and their negative effects on cooling and the environment will have to be reconsidered. A multiparameter packaging design approach considering cooling efficiency, mechanical performance, and effect of carton design on fruit quality is warranted to optimise the cold chain process of pomegranate fruit and the fruit industry as a whole. Such a well formulated design process will eliminate the randomness and reduce inneficiencies of the package designs used in the fruit industry.

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Declaration by the candidate

With regard to Chapter 6, pages 152–161, the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
Compiled and edited manuscript in its entirety throughout the publication process	75

The following co-authors have contributed to Chapter 6, pages 152–161:

Name	e-mail address	Nature of contribution	Extent of contribution (%)
Alemayehu Ambaw	tsige@sun.ac.za	Contributed to the conceptualisation of the research, supervised the research and edited the document in its entirety throughout the publication process	15
Umezuruike Linus Opara	opara@sun.ac.za	Conceptualised the study and edited the document in its entirety throughout the publication process	10

Declaration with signature in possession of candidate and supervisor **Signature of candidate**	16/08/2019 **Date**

Declaration by co-authors

The undersigned hereby confirm that:

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6, pages 152–161,

2. no other authors contributed to Chapter 6, pages 152–161 besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6, pages 152–161 of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019
Declaration with signature in possession of candidate and supervisor	Department of Horticultural Sciences, Stellenbosch University	16/08/2019

Chapter 6

A virtual prototyping approach for redesigning the vent-holes of packaging for handling pomegranate fruit

Abstract

In a previous study, experimental analysis and computational fluid dynamics (CFD) modelling were used to analyse the cooling performances of two corrugated fibreboard package designs (CT1 and CT2) for handling pomegranate fruit. In these analyses, the performance of the CT1 carton was shown to be low compared to the CT2 carton in terms of cooling rate, cooling uniformity and energy usage. The low performance of the CT1 carton was attributed to its improperly designed vent-holes. In the present communication, a virtual prototype approach, based on computational fluid dynamics (CFD), was used to redesign the CT1 carton for improved performance. This method enabled us to examine the thermal performance of new vent-hole configuration which was validated experimentally using the physical prototype of the new carton design. The new ventilation design resulted in 14.4% faster cooling of fruit and lowered pressure drop by 6.5% in fruit loaded cartons.

*Publication:

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6.1. Introduction

Fruit cold chain management is an interplay between the magnitude and uniformity of the cooling air, fruit-properties, package design, and stacking configurations (Berry *et al*., 2016). There has been renewed global interest in the development of cold-chain management systems, including ventilated packaging aimed at reducing postharvest losses, energy usage, and the carbon footprint (Opara, 2010).

The energy cost of refrigeration and to operate fans and blowers that drive cold air through stacked produce is profoundly affected by the packaging design. Attempts to enhance the energy performance of cold-chain processes through packaging design have shown significant potential (Defraeye *et al*., 2016; O'Sullivan *et al*., 2016; Ambaw *et al*., 2017; Mukama *et al*., 2017). Energy efficient ventilated packaging is the new focus of research through the use of vent-holes to achieve uniform and rapid cooling rates and yet without compromising the structural integrity of the packaging (Fadiji *et al*., 2016; Berry *et al*., 2017).

In corrugated fibreboard cartons, the vent-hole design affects the overall mechanical integrity of the cartons, unlike plastic crates. Fadiji *et al*. (2016) reported that the number, orientation, and shape of the vent-holes affected the buckling loads of cartons. The authors pointed out that rectangular vent-holes unlike circular ones better retain carton strength. Mitchell (1992) found that at carton vent-hole proportion ranging from 5–7%, the mechanical integrity of the carton becomes critically important. Additionally, Delele *et al*. (2013) observed reasonable increase in fruit cooling rates with ventilation area only up to 7% of the carton walls.

Recently, we examined the cooling performance of packaging (cartons) used for handling fruit in the pomegranate industry in South Africa (Ambaw *et. al*., 2017; Mukama *et. al*., 2017), and the result showed that the rate and uniformity of the precooling process and electricity costs were significantly affected by carton design. In these previous studies, we analysed the cooling performances of two corrugated fibreboard package designs (CT1 and CT2) (Ambaw *et al*., 2017; Mukama *et al*., 2017). The performance of the CT1 carton was lower than the CT2 carton in terms of cooling rate, cooling uniformity and energy usage, and the low performance of the CT1 carton was attributed to its improperly designed vent-holes. Particularly, it was demonstrated that due to the obstruction of the vent-holes during palletization of the cartons, there existed significant cooling heterogeneity with two distinctly different regions (high temperature and low temperature) inside the stack. We proposed to redesign the vent-hole location of this carton to alleviate the problem. Herein, we present results from the cooling performance of the new vent-hole design. The airflow, cooling rate, and cooling uniformity performances of the new design were compared to the existing counterpart.

6.2. Materials and methods

6.2.1. Fruit

Pomegranate fruit (*Punica granatum L*., cv. Wonderful) was procured from Sonlia Pack-house (33°34851” S, 19°00’360” E), Western Cape, South Africa. The pomegranates were 8.0 ± 0.2 cm in diameter and 358 ± 10 g in mass. Before the start of the cooling experiment, fruit were equilibrated to ambient air temperature (20 ± 3.0 °C).

6.2.2. Cartons

The dimensions and vent-hole locations of the currently used commercial design (CD) and the newly designed (ND) cartons are presented in Fig. 6.1 (a) and Fig. 6.1 (b), respectively. The CD has 6 semi-circular vent-holes along its long side located at the top and bottom rim of the sides and two vent-holes widthwise located at the top rim of the side. The ND carton was proposed based on virtually experimenting on vent-hole locations in such a way that vent-hole obstruction is avoided or minimized during stacking on the standard ISO pallet (1.2 x 1.0 m) (compare the free air path achievable along the front and sides of the ND, Fig. 6.1). The new vent-hole design aimed to provide more direct air stream into the stack during forced air cooling and thereby reduce cooling non-uniformity (Fig. 6.2). The ND has 3 and 2 vent-holes along the long and short sides, respectively.

Table 6.1 summarizes the fruit loading capacities and vent area characteristics of the cartons. Plastic wrapping was done by placing pomegranates in a single non-perforated 10 µm thick high-density polyethylene (HDPE) plastic film.

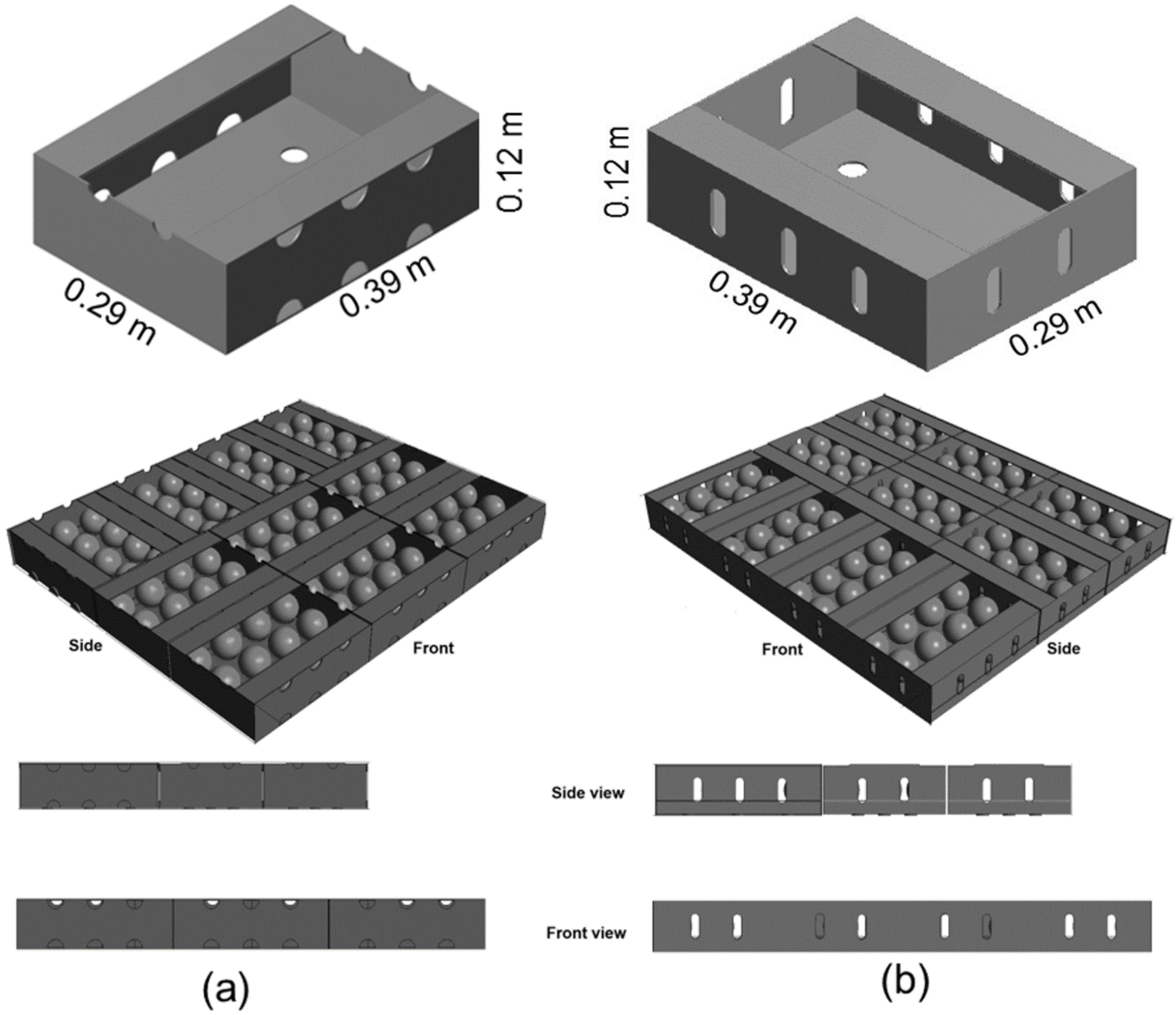

Fig. 6.1 Schematic diagram showing the dimensions (top row), stacking patterns (second row), vent-hole obstructions along the sides (third row), and vent-hole obstructions along the front (bottom row) of the current commercial design (CD) (a) and the new design (ND) (b) cartons

Table 6.1 Package dimensions, vent-hole ratios, and loading of the current commercial design (CD) and new design (ND)

		Vent-hole ratio [%]			**Loading**	
Design	Dimensions [m]	Short side	Long side	Bottom side	Number of fruit	Total weight [kg]
CD	0.39 × 0.29 × 0.12	2.0	8.0	3.0	12	4.3
ND	0.39 × 0.29 × 0.12	7.3	7.9	3.0	12	4.3

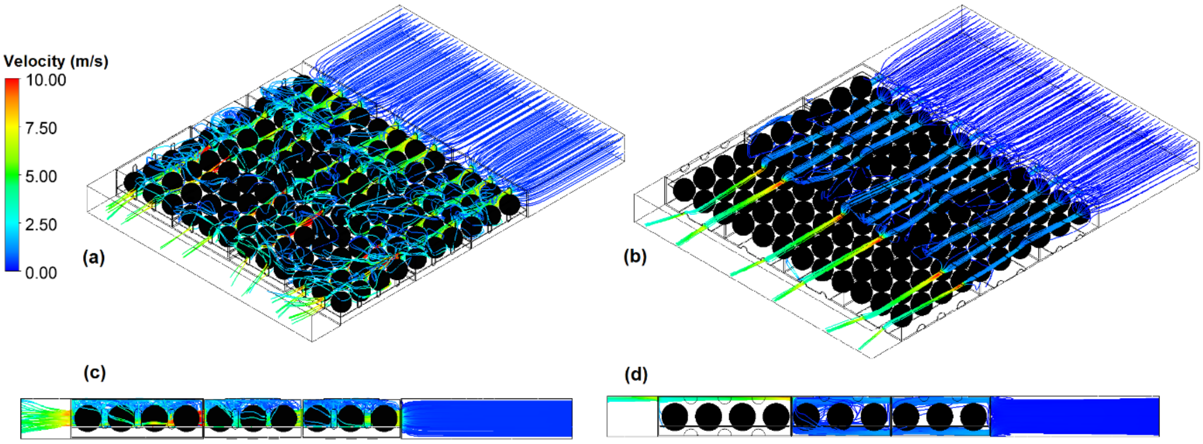

Fig. 6.2 Schematic showing simulated airflow distribution in stack of (a) new design cartons (ND) and (b) current commercial design (CD). (c) Side view of ND and (d) side view of CD

6.2.3. Measurements

6.2.3.1. Resistance to airflow

The resistance to airflow (RTA) was measured based on the method described by Mukama *et al*. (2017). RTA measurements were made for the empty carton, cartons loaded with fruit with no liner, and cartons loaded with fruit wrapped with polyline. Measurement was made on one layer of carton and cooling air was drawn through the 1.2 m side of the setup.

6.2.3.2. Measuring the cooling characteristics

The cooling characteristics were measured by monitoring fruit core temperatures of sample fruit in each carton (Fig. 6.3). Cooling air at 7 °C was drawn through the 1.2 m side of the stack. The forced air cooling set up was as in (Mukama *et al*., 2017) but for one layer of cartons.

6.2.3.3. Numerical modelling

Computational fluid dynamics (CFD) modelling of the temperature distribution for the CD and ND was done as described by Ambaw *et al*. (2017). The thermal properties of pomegranate fruit used in the heat model were obtained from Chapter 3. The analysis was done on pomegranate fruit packed with no liners inside the carton.

6.2.4. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 13 (StatSoft, Inc. Oklahoma, USA). Means were separated using Duncan's multiple range tests (Factors: carton design and lining).

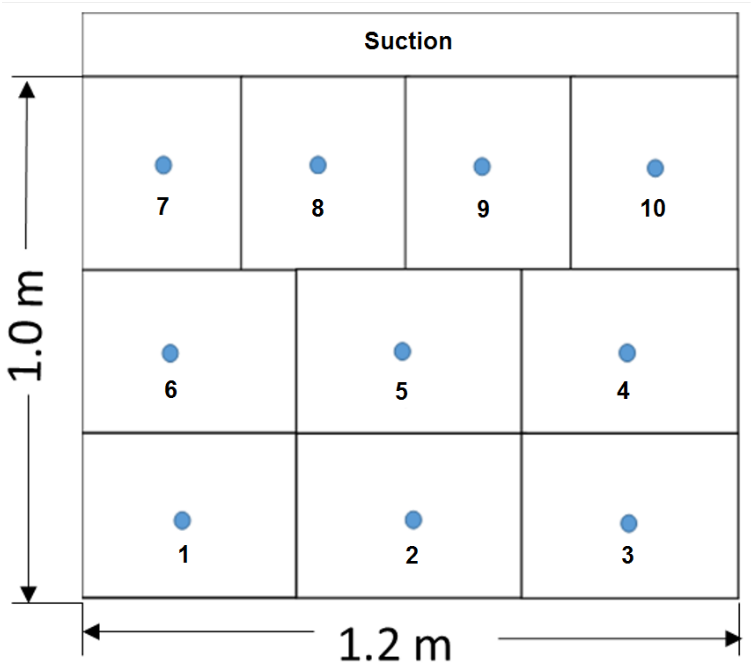

Fig. 6.3 Schematic showing layout of cartons and location of data logged sample fruit

6.3. Results and discussions

6.3.1. Effect of carton design and polyliner on pressure drop

The pressure drop pattern of the ND in comparison to the CD is shown in Fig. (6.4). Generally, the ND had relatively lower pressure drop compared to the CD, which implies that the vent-hole modification on the ND enabled easier airflow channelling in the carton layer compared to the CD. For example, taking superficial air velocity 1.25 m s^{-1}, the measured pressure drop (Pa m^{-1}) was 380 and 385 for empty ND and CD, respectively, 435 and 466 for no liner packaging in ND and CD, respectively, and 580 and 620 for fruit in polyline in ND and CD, respectively (Fig. 6.4). The order of pressure drop was liner > no liner > empty, which corroborated the observations by Mukama *et al*. (2017) and Ambaw *et al*. (2017).

6.3.2. Cooling characteristics – temperature distribution

Modification of vent-holes in the new design resulted in improvement in the uniformity of temperature distribution (Fig. 6.5). The variation in cooling rate of fruit in the 3rd row (high temperature region) from the air inlet side observed in the CD (Fig. 6.5 (a)) is solved in the ND (Fig. 6.5 (b)). This is because of better alignment of the vent-holes in the new design on stacking the cartons enabling easier airflow channelling across the stack effecting faster and more uniform cooling of pomegranate fruit. However, the experimental results showed slight and generally insignificant cooling time differences across the layer, in liner (Fig. 6.6) and no liner (Table 6.2) packaged fruit.

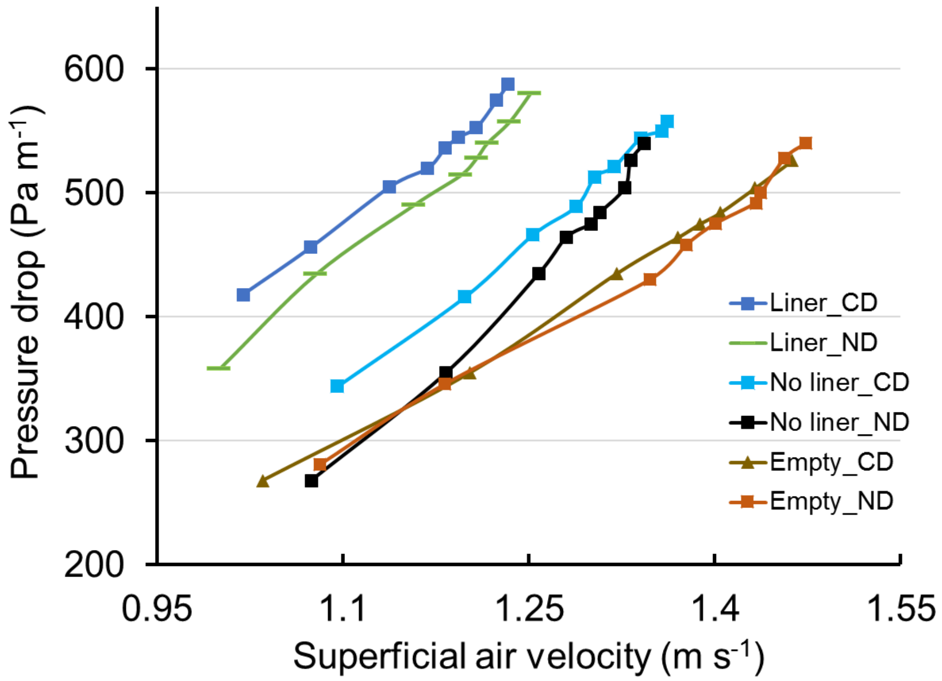

Fig. 6.4 Experimental pressure drop vs. flow rate data of forced airflow through one layer of stack of pomegranate fruit in the new design (ND) and the current commercial carton design (CD)

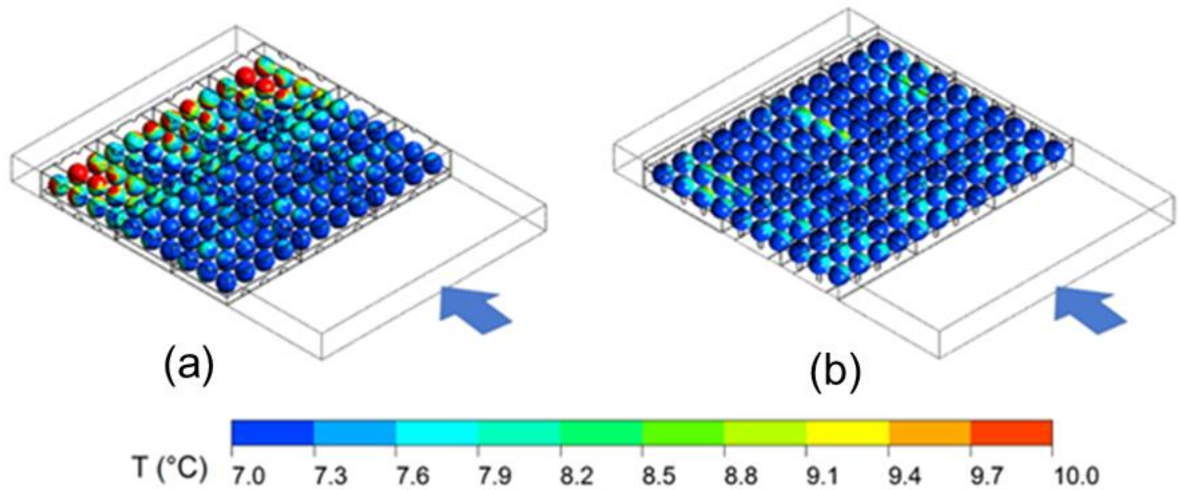

Fig. 6.5 Simulated temperature distribution in a layer of (a) CD and (b) ND stacks with no lining. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}, air temperature 7 °C

Generally, fruit in ND with no liner cooled significantly faster (in 2.85 hours) than fruit in the CD (3.33 hours). The seven eighths cooling time variability among the temperature logged fruit with no liner in the ND was also lower than for fruit in the CD (Table 6.2). Fruit cooling rates followed a similar trend as observed by Mukama *et al*. (2017) and Ambaw *et al*. (2017), with fruit upwind cooling relatively faster than those at the back of stack from the air inlet side (Table 6.2).

Fruit cooled in liners took significantly longer to cool down (Fig. 6.6). Taking on average 8.1 hours longer compared to fruit in no liner in both the ND and CD. Cooling rates of polylined fruit are influenced primarily by the temperature of the cooling air and to a lesser extent the airflow distribution (O'Sullivan *et al*., 2016). A similar trend of improved cooling performance was observed in fruit in polyline where fruit in the ND cooled on average in 10.4 hours while fruit in CD cooled in 12.0 hours. Additionally, fruit upwind cooled relatively faster than fruit at the back of the stack from the air inlet side (Fig. 6.6). However, the difference in cooling time was larger in fruit in polyline (7.3 hours) compared to fruit in no liner (2.4 hours).

Table 6.2 Experimental seven eighth cooling time (SECT) of pomegranate fruit cooled with no liner in the current commercial cartons (CD) and new carton designs (ND)

	SECT (h)		**Percentage difference in SECT**
Fruit sample location	**CD**	**ND**	
1	1.7 ± 0.1^{i}	1.3 ± 0.1^{j}	26.7
2	2.5 ± 0.2^{g}	2.0 ± 0.2^{hi}	22.2
3	2.6 ± 0.1^{fg}	2.4 ± 0.1^{gh}	08.0
4	3.4 ± 0.2^{e}	2.6 ± 0.3^{fg}	26.7
5	3.6 ± 0.1^{bcde}	2.9 ± 0.2^{f}	21.5
6	3.8 ± 0.2^{abcd}	2.9 ± 0.4^{f}	26.9
7	3.9 ± 0.1^{abc}	3.4 ± 0.1^{de}	13.7
8	4.0 ± 0.1^{ab}	3.8 ± 0.5^{abcde}	05.1
9	3.9 ± 0.3^{abc}	3.5 ± 0.2^{cde}	10.8
10	4.1 ± 0.2^{a}	3.8 ± 0.3^{abcd}	07.6

Values mean ± standard deviation of 3 replicates. Different letters indicate significance difference. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}

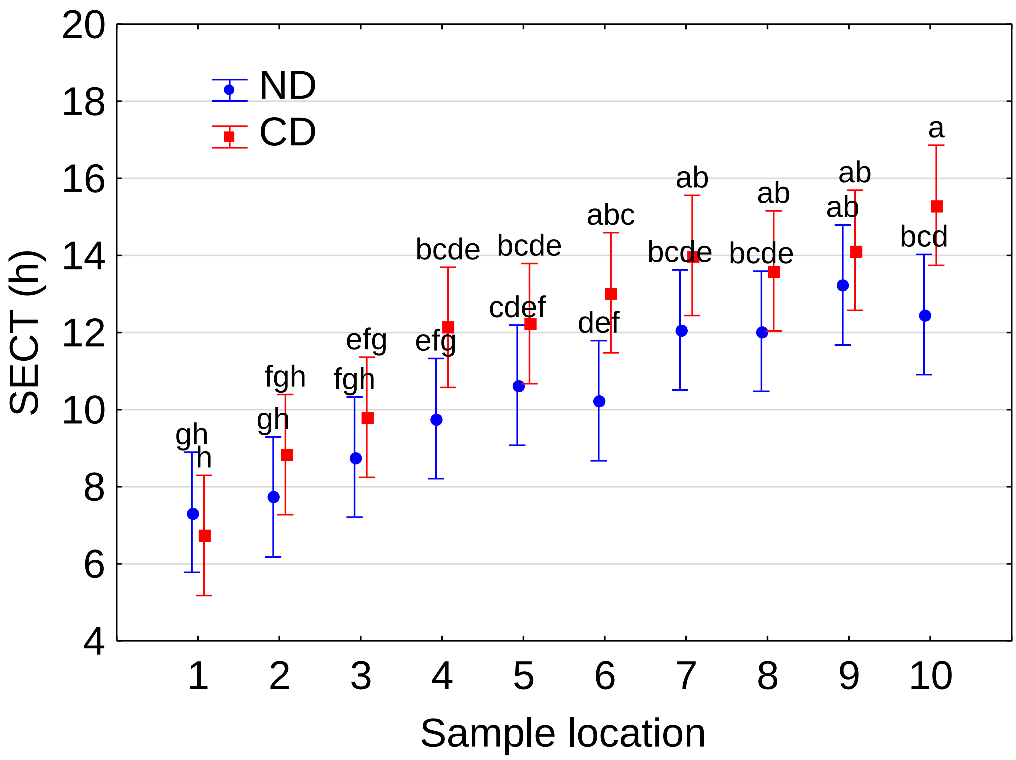

Fig. 6.6 Experimental seven eighth cooling time (SECT) of pomegranate fruit in polyline per sample location in the current commercial cartons (CD) and new carton designs (ND). Verticle bars denote 0.95 confidence intervals of 3 replicates. Different letters indicate significance difference. Cooling was done at constant airflow rate of 0.5 L kg^{-1} s^{-1}, air temperature 7 °C

6.4. Conclusion

The application of computational fluid dynamics for conducting experiments on the virtual prototype combined with experimental testing helped to perform important parametric studies. This is based on the exponential growth of computer power in recent years that has eased the tedious nature and cut costs and time required to perform experiments. Therefore, different and complex scenarios are quickly and cheaply virtually tested before a validation experiment is later conducted. Fruit cooled in the ND had more uniform temperature distribution and significantly cooled faster compared to fruit in the CD. The ND carton also recorded lower pressure drop in the forced air cooling operation (over 35.3 Pa m^{-1} less, in cartons with fruit). Fruit wrapped in a polyliner took 8.1 hours longer to cool than fruit with no liner. The results from this study demonstrate the influence of vent-hole design on the cooling characteristics of fruit. By ensuring unobstructed airflow in the stack of fruit during precooling, the performance of the fruit cooling process is significantly improved.

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Chapter 7

Integration of virtual and physical testing in packaging design for better space usage and increased throughput in the cold chain management of pomegranate fruit: Part 1, virtual designs

Abstract

Virtual prototyping is a fast and cost effective product design approach. Proper design of cartons used in fruit handling may improve the overall handling efficiency, volumes, and reduce overall costs to the fruit industry. In this study, a virtual prototype approach, based on computational fluid dynamics (CFD) and computational solid dynamics (CSD), was used to design new ventilated corrugated fibreboard cartons that hold pomegranate fruit in two layers. Running virtual tests enabled quick assessments of the airflow and mechanical performance of different corrugated fibreboard carton design scenarios and prototypes based on available literature on the aspects of ventilation shape, size, area, and position on the carton, and carton stacking. Following different trials, the best alternatives of the several proposed conceptual models—two new designs, 'Edgevent', and 'Midvent' were compared on aspects of shipping density and material utilisation. The new virtual designs improved cargo density by over 1.8 tons more fruit in a refrigerated container compared to commercial carton (9.5% improvement). For similar volume of fruit contained, the 'Edgevent' and 'Midvent' saved over 31% fibreboard material and an estimated equivalent of 11 trees per fully loaded 40-ft reefer. Therefore, the virtual prototyping approach provides new opportunities in the design of ventilated corrugated fibreboard cartons that improve the efficiency of the cold chain. This approach is thus recommended for future carton design processes to save costs involved in manufacturing designs prototypes that may turn out inefficient because the design process was not detailed and comprehensive.

7.1. Introduction

There is an increasing trend towards reduction in time and costs required in new product design and developments (Zorriassatine *et al*., 2003; Gibson *et al*., 2004; Huang *et al*., 2007). The continuous growth in computer power has eased such developments through the use of virtual prototyping and testing, before production of physical prototypes (Gibson *et al*., 2004). Virtual prototyping involves creation of precise virtual models and scenarios in the conceptualisation process, envisaging real circumstances which are then transformed into physical processes after rigorous and satisfactory virtual performance (Huang *et al*., 2007). This engineering design approach was pioneered in the automotive and aerospace industries (Zorriassatine *et al*., 2003), but is used currently across sectors including construction, and even in the field of postharvest packaging (Wu *et al*., 2018, 2019). The major virtual technologies in use in the postharvest include computational fluid dynamics (CFD), computational thermal dynamics (CTD), and computational solid dynamics (CSD). These tools allow creation of models that allow exact control of operating parameters while providing vital information like the airflow, mechanical stress, mechanical strain, and temperature patterns within the stack of fruit under refrigeration conditions; providing mechanisms and performance details of the processes (O'Sullivan *et al*., 2016; Fadiji *et al*., 2018; Wu *et al*., 2019).

Packaging is a key food processing unit operation serving functions of containment, protection, preservation, storage, and distribution of food (Robertson, 2013). Food packages are made from plastic, wood, but paper, corrugated board, and other fibreboard package materials account for 1/3 of the global packaging trade (Rundh, 2005; GADV, 2019; Opara & Mditshwa, 2013). The horticultural industry uses millions of fibreboard cartons to move produce around the world annually. These hold produce in single or multiple layers, have different vent-hole configurations, and are made from a variety of paper materials with different flute/liner configurations. However, the designs of these cartons in most cases are through trial and error (Berry *et al*., 2105), instead of a design optimisation process that considers and evaluates the materials used, internal packages, effects of vent-hole designs on the mechanical properties, fruit cooling properties, and cold chain energy efficiency (Defraeye *et al*., 2015; Berry *et al*., 2016, 2017). Such a design analysis is termed a multiparameter approach (Berry *et al*. 2017).

Fruit cold chain management is an interplay of the cooling air properties, fruit properties, packaging, and stack configurations. The complexity of air movement inside stacks of cartons and around individual fruit makes experimental measurements and information of local airflow, heat, and mass transfer very difficult, time consuming, and challenging. Horticultural products are mostly stacked/palletised and handled under conditions of low temperature, high humidity (cold chain) during storage and transport. Palletisation is meant to ease the handling and movement of the packaged fruit (Chen *et al*., 2011) and minimises damage to fruit because of reduced individual carton handling. Therefore, the cartons used are meant to perform and withstand these conditions to deliver produce at the best quality to the table. It thus requires that compression tests are undertaken on all new designs to determine suitability to this practice (Pathare & Opara, 2014).

Fresh produce cartons are designed with vent-holes, essential to ensure that cold air at the required temperature is delivered inside the package during cold chain handling as well as ensuring outflow of the heat of respiration from the fruit (Zou *et al*., 2006a, b; Opara & Mditshwa, 2013). These vents serve to efficiently deliver cooling air to the produce during forced air precooling, which is the most widely employed precooling method in the horticultural industry. Vent shape, area, position on carton, number, and how the whole ventilation aligns out in stack of cartons affect the aerodynamics of the system. This translates to the time it will take to cool the fruit, the homogeneity of cooling, and the energy requirements for the whole process (Dehghannya *et al*., 2012; Defraeye *et al*., 2014; Ambaw *et al*., 2017; Mukama *et al*., 2017).

Fruit are largely heterogeneous products, requiring unique handling tools and conditions. Previous studies have investigated and, or created new designs for postharvest handling of fruit in the cold chain, for example: apple (Berry *et al*., 2017), mango (Chonhenchob & Singh, 2003; Singh *et al*., 2013), straw berries (Ferrua & Singh, 2009, 2011), rose apples (Jarimopas *et al*., 2007), papaya (Chonhenchob & Singh, 2005), sweet tamarind (Jarimopas *et al*., 2008). Singh *et al*. (2011) developed new packaging design for straw berries that improved the uniformity and energy efficiency of the forced air cooling process by a 70% reduction in the pressure drop across the system. Other researchers like Chonhenchob & Singh (2003), Jarimopas *et al*. (2007), Chonhenchob & Singh (2005) focussed more on designs that reduce mechanical damage during transportation of mangoes, rose apples and papaya to the markets. However, very limited research is available on pomegranate fruit packaging. Additionally, most other horticultural fruit for example apples, pears, plums, etc. are packaged in multiple layers within a single carton (Berry *et al*., 2015). This increases the shipping density and space usage of these fruit in cold stores and refrigerated containers, unlike pomegranate fruit (Mukama *et al*., 2017).

Recent studies by Ambaw *et al*. (2017) and Mukama *et al*. (2017) on carton designs used in the South African pomegranate industry found that the efficiency of the pomegranate fruit cold chain is largely affected by package design. The cartons held fruit in single layers and exhibited different cooling rates and cooling uniformities largely affected by ventilation design and orientation of the ventilations in fruit stacks. Particularly, one of the carton designs (CT1) exhibited poor fruit cooling characteristics and energy inefficiency—required 1.5 fold more energy due to obstruction of vent-holes on stacking. Additionally, Ambaw *et al*. (2017) noted that pomegranate fruit are loosely packed in cartons compared to other fruit like apples, and thus aerodynamic and thermodynamic performances during forced air cooling of pomegranate fruit depends considerably on package design and not resistance from fruit.

In this study, a virtual prototype approach (Fig. 7.1), based on CFD, and CSD was used to design new ventilated corrugated fibreboard cartons (CFC) that hold pomegranate fruit in two layers. CFD has been used as a virtual tool to verify the airflow of packaging box designs and assess several cold-chain management processes in the fresh fruit packaging industry. (Ambaw *et al*., 2013, 2017; Delele *et al*., 2013; Defraeye *et al*., 2015; Berry *et al*. 2016, 2017). CSD on the other hand has been used to determine mechanical integrity of horticultural packages under different handling conditions (Han & Park, 2017; Fadiji *et al*., 2017, 2018, 2019). The virtual tools were used to assess the airflow and mechanical performance of several virtual designs, with intent to design new fibreboard cartons that can cool pomegranate fruit faster and more uniformly, improve the fruit throughput and space utilization in the pomegranate fruit cold chain, especially in transit (shipping density), and could generally reduce material, energy, and handling costs. By running a virtual test, which took only few hours, it was possible to find an accurate measure of design parameters and detailed visualization of airflow contours and streamlines.

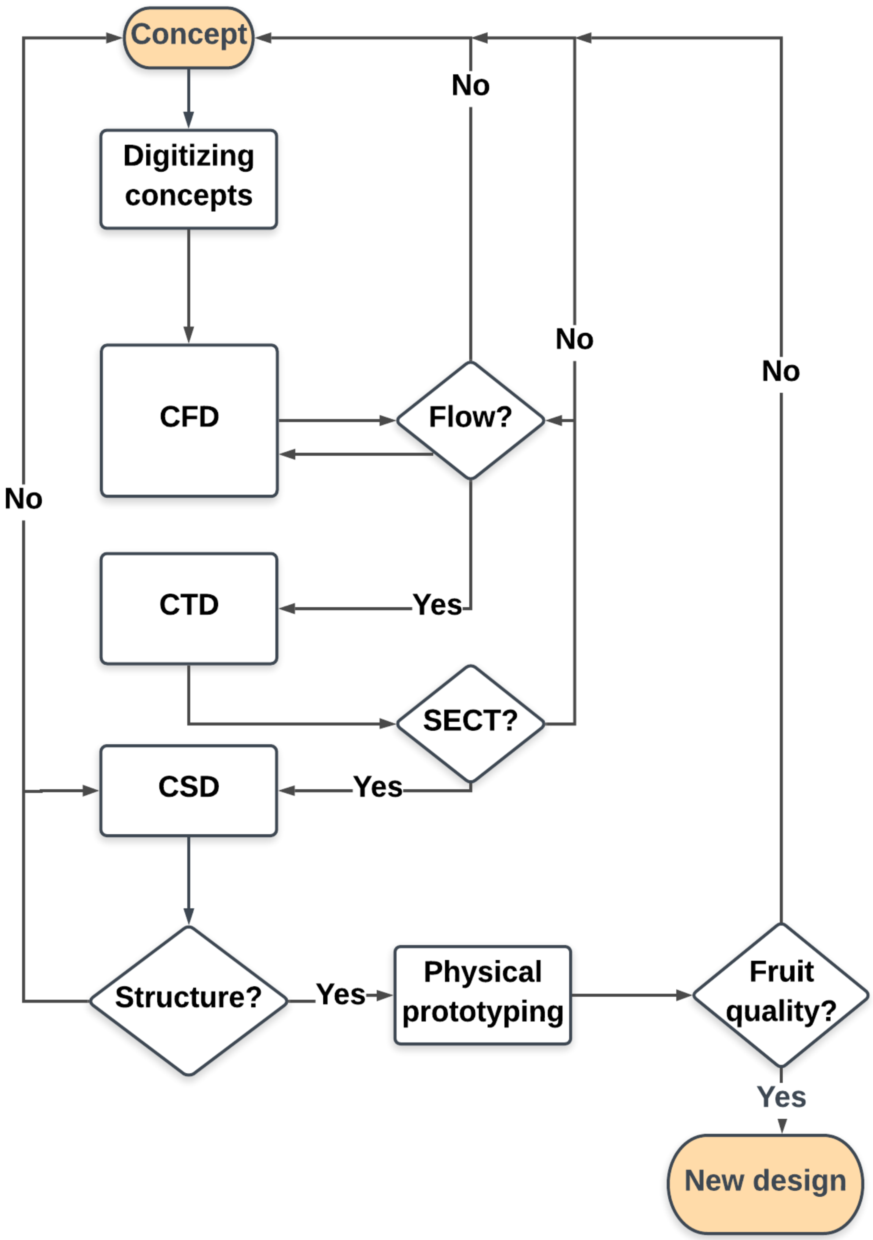

Fig. 7.1 Schematic showing a virtual prototyping design approach for fruit packages from concept to design. CFD – Computational Fluid Dynamics, CTD – Computational Thermal Dynamics, CSD – Computational Solid Dynamics, and SECT – Seven eighths Cooling Time

7.2. From concept to geometric models

Geometric models of the produce, individual carton, fruit loaded carton, loaded cartons as stacked on a pallet, and palletized stacks as arranged in a processing unit (cold storage unit, precooling system, reefer or integral containers for fresh fruit transport) were obtained. New packaging cartons proposals were guided through virtual prototyping of selected conceptual designs. The size and dimensions of individual cartons depends on the physical (size, shape, structure) and physiological (respiration, transpiration, and ripening) characteristics of the fruit to be contained. Sizing and dimensioning of the carton should be in cognizance of the standards and market regulations. In this case, the carton foot-print (bottom dimensions 395 × 295 mm) was maintained for all the tested virtual models, similar to the most widely used cartons in industry. One of the main study aims was to achieve comparatively high cargo density, therefore, the carton design models were multilayer with consideration of individual pomegranate fruit weights (400–500 g).

Fig. (7.2) depicts the virtual geometric dimensions of 'Class 1 fruit' of the most exported cultivar of pomegranate fruit in South Africa ('Wonderful'), used to determine the carton dimensions. The 3D geometry of the pomegranate fruit as arranged on fruit trays was generated based on CT scan of individual fruit. Then computer graphic tool was used to create the 3D geometry of one box filled with 9 kg pomegranate fruit. The simplified geometry of stacked pomegranate fruit ready for the CFD analysis is shown in Fig. (7.3).

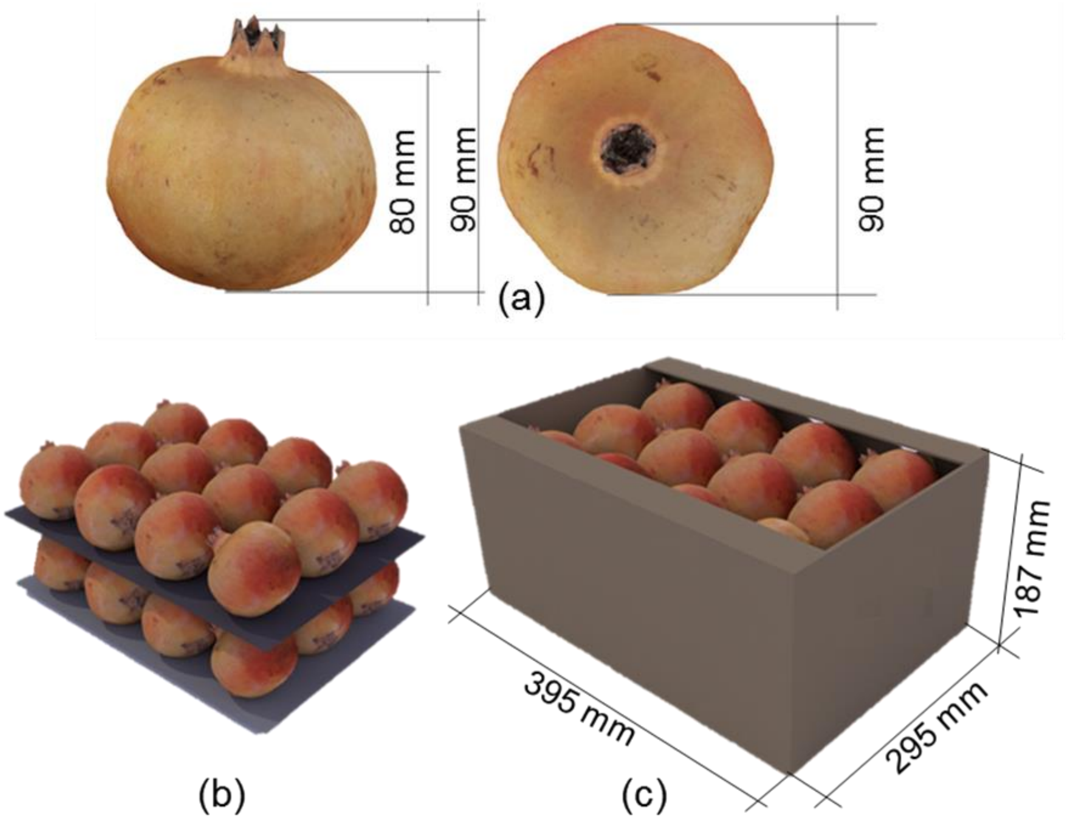

Fig. 7.2 Schematic showing (a) geometric dimensions of 'Class 1 fruit' (cv Wonderful) (b) model of a 2 layer stack of pomegranate fruit for a single carton separated by a tray (c) dimensions of a 2 layer carton

Ventilation design of the model cartons was based on the package design principles from literature in Table 7.1. Vent-hole alignment both vertical and horizontal (Fig. 7.3) was also a principal virtual design concept to ease airflow and ensure even air distribution within the stack that was found lacking in pomegranate fruit cartons studied by Mukama *et al*. (2017) and Ambaw *et al*. (2017). Pomegranate are packed on trays, therefore in the models, vent-hole blockage by the tray and middle vent-hole addition to ensure airflow within the fruit multilayer was considered.

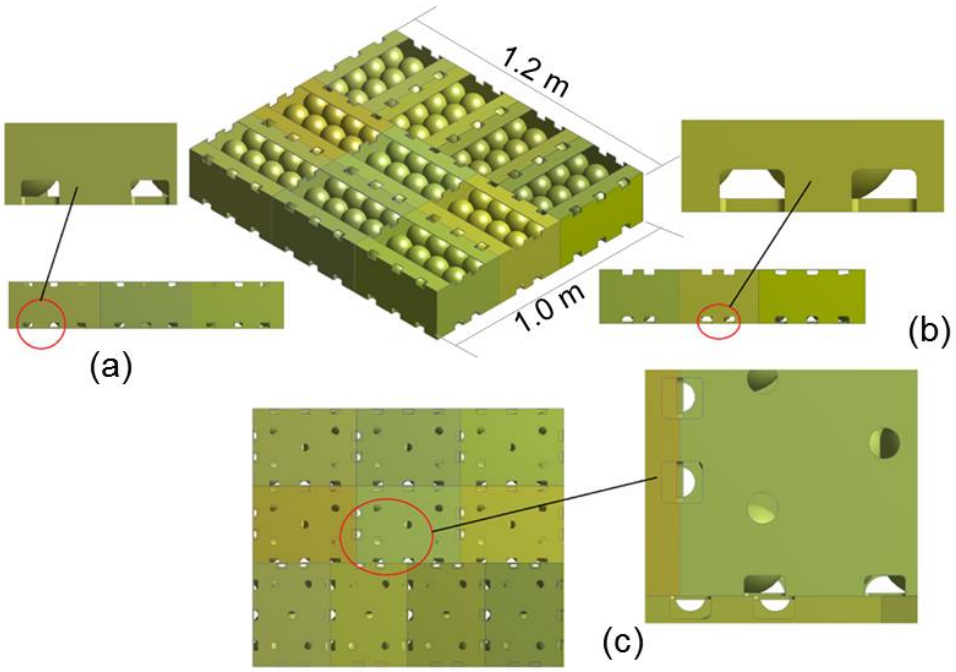

Fig. 7.3 Simplified geometry of stacked pomegranate fruit ready for the CFD analysis (a) the ventilation of cartons on 1.2 m side of standard pallet stack, (b) ventilation on the 1.0 m side (c) ventilation on the bottom of the stack

Table 7.1 Corrugated fibreboard carton (CFC) design considerations and recommendations from literature for mechanical integrity and cooling efficiency

Carton characteristic	Main finding(s)	Reference(s)
Vent shape	Ventilation holes with a vertical oblong shape produced smaller stress level, the least surface area of stress concentration, and had the highest structural stability against compression	Han *et al*. (2007)
Vent Shape	Vent-holes are blocked by fruit of similar shape. For example, round fruit are more likely to block the vent holes if placed in cartons with round vent holes	Thompson *et al*. (2008)
Vent Shape	Rectangular vents generated 8.4% more pressure drop compared to circular vents, but the shape did not affect the uniformity of airflow and the cooling characteristics (rate and uniformity) of the produce	Delele *et al*. (2013)

Table 7.1 *Continued*

Carton characteristic	Main finding(s)	Reference(s)
Vent shape	Rectangular and parallelogram vent-holes had higher compressional strength than circular vent-holes	Singh *et al*. (2008)
Vent area	Increase in vent area of CFC beyond 8% did not significantly increase the cooling rate	De Castro *et al*. (2004)
Vent area	Increase in vent area of CFC beyond 7% did not significantly increase the cooling rate	Delele *et al*. (2013)
Vent area	Best cooling efficiency was obtained with an open ventilation area of between 8 to 16% of the carton walls	De Castro *et al*. (2005a)
Vent area	Cartons with vent area above 5% require careful design to achieve mechanical integrity of CFC	Mitchell (1992)
Vent area	There was 0.56–1.08% reduction in structural strength following a 1% increase in vent area of corrugated carton	Singh *et al*. (2008)
Vent area	A minimum of 5% vent area of the carton side walls is required for minimum airflow restriction during forced-air cooling	Thompson *et al*. (2008)
Vent area	Loss in carton strength varied linearly with total vent area	Singh *et al*. (2008)
Vent size	Vents need to be 10 mm wide or more because chances of blockage of vents smaller than 10 mm by the produce are higher	Thompson *et al*. (1998)
Vent position	To minimise loss in the mechanical strength of cartons, vents should be 40 to 70 mm away from all carton corners	Thompson *et al*. (2008)
Vent position	There was a 14.6% decrease in pressure drop on placing vents to the top and bottom of the carton compared to the centre	Delele *et al*. (2013)
Vent position	Top and bottom positioned vents increased the airflow uniformity compared to centre and corner positioned vents	De Castro *et al*. (2005b)
Vent position	Carton vents should not be positioned in corners as this affects airflow uniformity and increases energy requirements during forced-air cooling	De Castro *et al*. (2005b)
Vent-hole distribution	Improper vent distribution on cartons increased the cooling heterogeneity even with higher percentage ventilation	Dehghannya *et al*. (2012)
Hand-holes	Hand holes should be at least 70 mm in length	Han *et al*. (2007)
Presence/absence of vent-holes	There was 20–50% loss in strength of single wall CFC due to presence of vent and hand holes	Singh *et al*. (2008)

7.3. Visualising and quantifying the airflow using CFD

Computational fluid dynamics (CFD) modelling of the airflow distribution in the models was done as described by Ambaw *et al*. (2017). For each flow configuration, first the flow across individual box was investigated. This helps to evaluate the contribution of individual vent-holes to the total flow. Then, the airflow of palletized boxes during precooling (horizontal flow) and transport (vertical flow) were investigated.

Fig. 7.4 depicts the velocity streamlines corresponding to horizontal airflow across a single box and pallet stack of cartons with airflow perpendicular to 1.0 m pallet orientation (air flows from left to right). There are four half-circular and two oblong vent-holes at the inlet and at the outlet (Fig. 7.4 (a). In a stack, these are aligned perpendicular to the horizontal flow. The circular and half circular vent-holes at the bottom of the stack (Fig. 7.3 (c)) enable vertical airflow in the stack (Fig. 7.5).

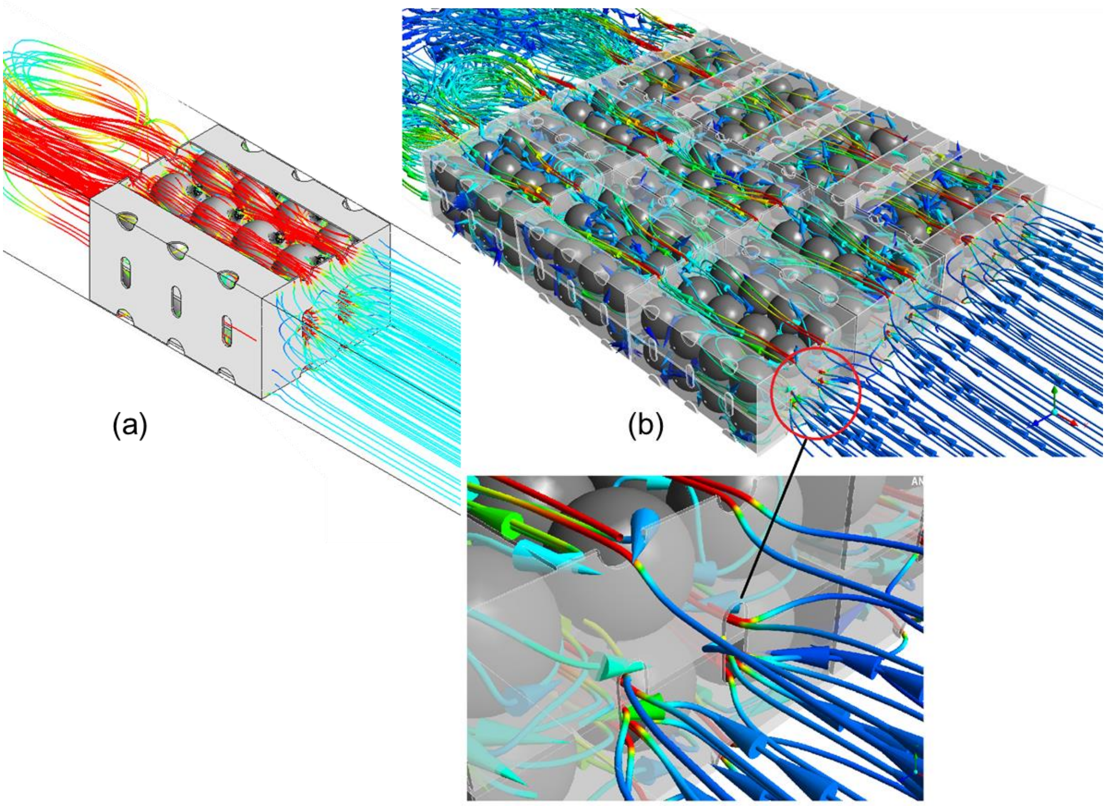

Fig. 7.4 Horizontal airflow streamlines through (a) single carton (b) stack of cartons on standard pallet

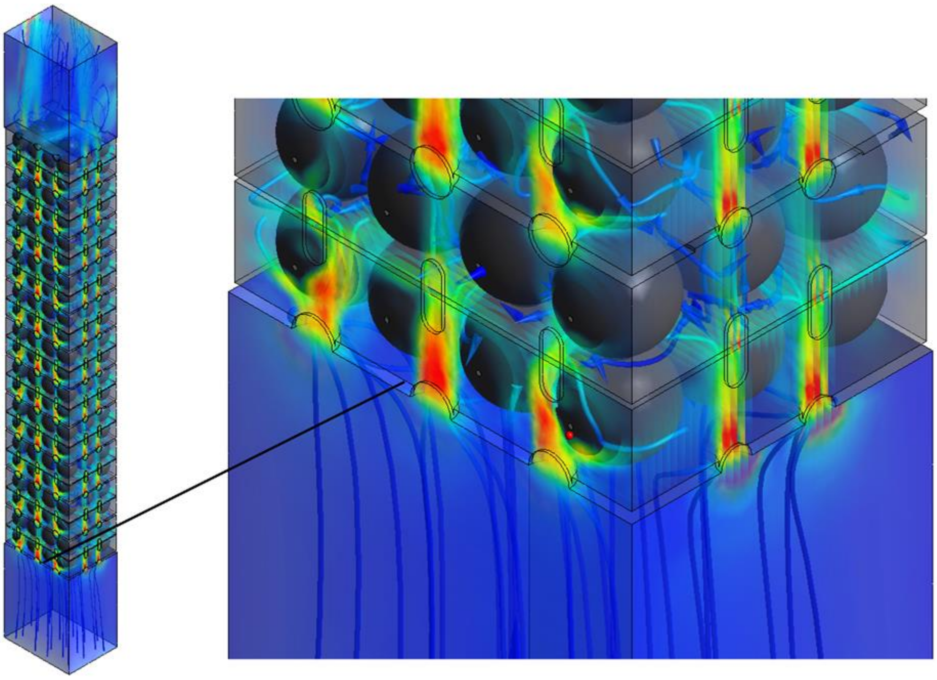

Fig. 7.5 Vertical airflow streamlines through a column of cartons on a pallet stack

From the CFD airflow simulations, the best performing designs were the 'Edgevent' and the 'Midvent' (Fig. 7.6). The vent-hole and ventilation area of these designs are shown in Table 7.2 and Table 7.3, respectively. The 'Edgevent' had three vent-holes along the top and bottom of the long side and two along the bottom and top of the short side. The 'Midvent' had a similar ventilation pattern but with additional oblong vents in the middle of the carton, three on the long and two on the short side (Fig. 7.6).

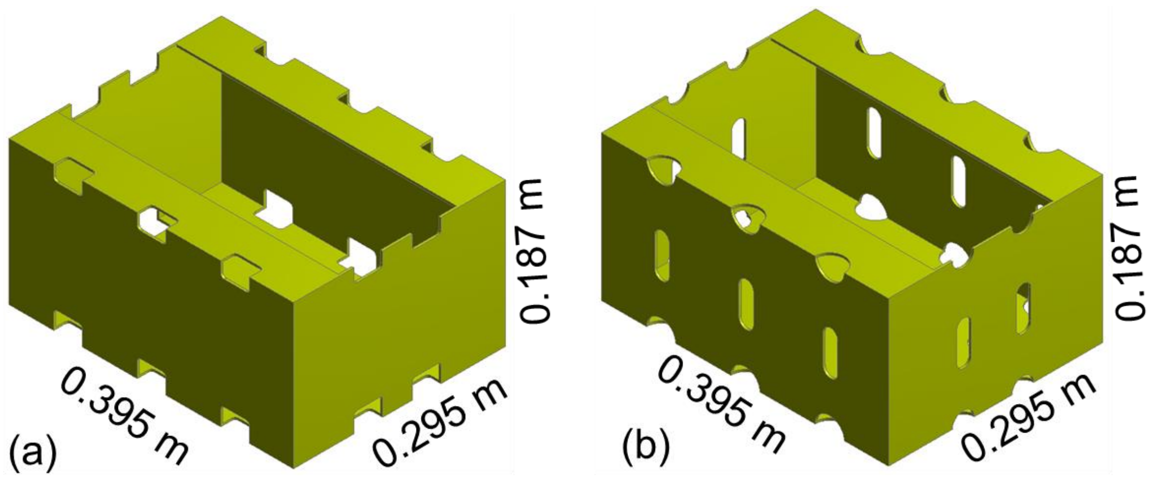

Fig. 7.6 Schematic showing the (a) 'Edgevent' and (b) 'Midvent' carton designs

7.4. Investigating carton structural integrity using CSD

Corrugated fibreboard packages must support considerable mechanical loads during long term cold storage and transport of fresh produce in refrigerated freight containers. This is done within conditions of low temperature and high humidity. In industry, the required strength of the cartons for fruit cold chain handling is calculated based on the formula (Grobbelaar, D, 2018, Structural designer, APL Cartons, Worcester, South Africa, Personal communication, 20 September):

Required Strength = weight of one loaded carton × number of cartons on top of bottom carton × factor (3 for local market and 4.5–5 for export market) × g (acceleration due to gravity).

The new designs loaded with fruit weighed about 9 kg gross weight and were stacked 11 cartons high per pallet. Thus, taking a factor of 5, the new carton design placed at the bottom of the pallet is required to withstand a force of 4500 N without buckling.

7.4.1. Finite element analysis

Finite element analysis (FEA) was used to determine the structural stability of the new carton designs. The geometry was developed using ANSYS® Design Modeller™ Release 18.1 (ANSYS, Canonsburg, PA, USA). Meshing and numerical analysis were done using software: MSC Patran (MSC Software Corporation, CA, USA) and Mentat/Marc (MSC Software Corporation, California, USA), respectively. Liner elastic 3D orthotropic properties were used to model the corrugated fibreboard carton. Material properties were used as input parameters in the finite element simulation. The properties for both ambient and cold conditions were obtained from Fadiji *et al*. (2019) and Fadiji *et al*. (2017). In order to capture bending and the actual pattern of the fibreboard of liners and the core properly, cartons were oriented properly, and quadrilateral shell elements were used for the simulation. For the FEA simulation, the carton was modelled as a composite structure consisting of three layers where a solid core was created (Fadiji *et al*., 2019). Mesh size used for the model was 4 mm.

The top of the package was constrained along the lengthwise (long) side of the package to allow for translation in the *y* direction while the translation in the *x* and *z* directions was prevented. Rotation in the *y* and *z* direction was fixed while the rotation in the *x* direction was allowed. Similarly, along short side of the package, translation in the *y* direction was allowed, while the translation in the *x* and *z* directions was fixed. However, unlike the long side of the package, rotation was fixed in the *x* any *y* directions while rotation in the *z* direction was allowed. Face pressure was applied to the top of the package. At the bottom of the package, translation and rotation were fixed in all directions (Fig. 7.7). Linear buckling analysis was carried out to determine the critical buckling load and estimate the most likely buckling shape of the package.

7.4.2. FEA simulation results

Fig. (7.8) and Fig. (7.9) show the plots of the buckling mode for the 'Midvent' and 'Edgevent' carton designs at ambient and cold conditions, respectively. The FEA plots showed the origination of buckling from the centre of the cartons, with an outward bow observed on the long side of the carton. However, the short side of the carton showed more resistance to buckling. This failure phenomena has been attributed to localised crushing of the carton boards (Fadiji *et al*., 2019; Panyarjun & Burgess 2001). The model maximum compression force for the 'Midvent' was 8331 N and 6224 N at ambient and cold conditions (Fig. 7.8), while that of the 'Edgevent' was 7251 N and 5867 N at ambient and cold conditions respectively (Fig. 7.9). This is an equivalent of 25.29% and 19.09% loss in carton strength in the 'Midvent' and 'Edgevent', respectively, at cold conditions due to absorption of water by the cellulose fibres at high relative humidity in the cold chain (Zhang *et al*., 2011).

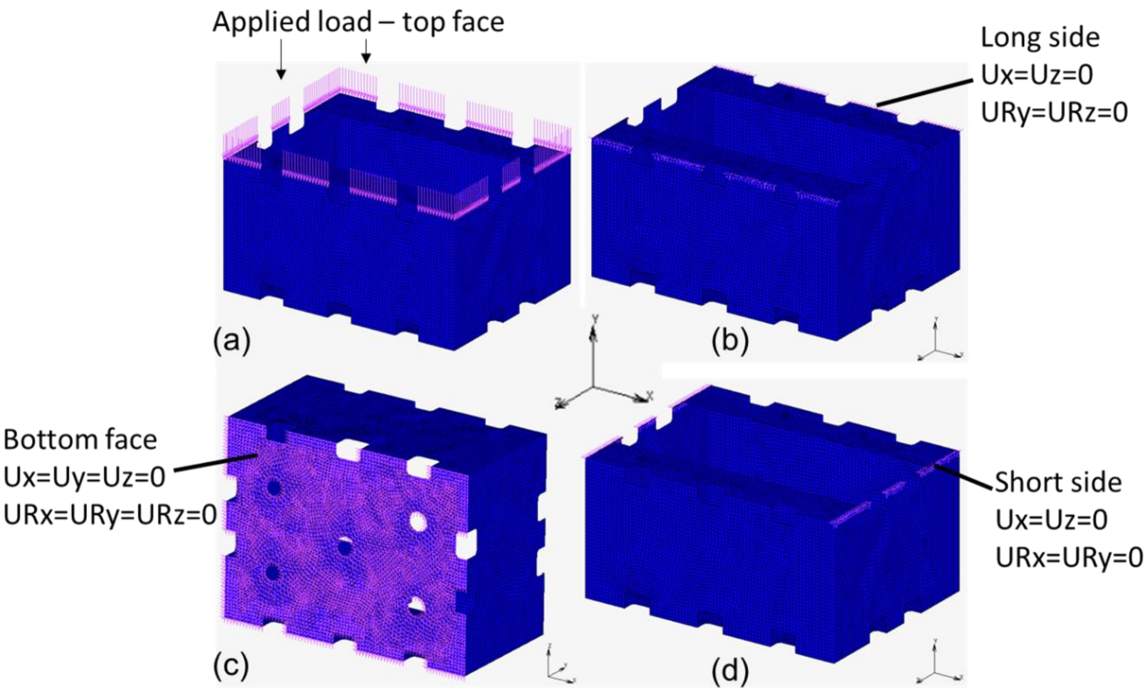

Fig. 7.7 Schematic showing the boundary conditions (constraints) applied on the cartons during the Finite Element Analysis (a) compression load on top, (b) long sides, (c) bottom face, (d) short sides. Ux, Uy, and Uz are the displacements in the x, y, and z directions, respectively. Ux = 0 means the displacement was fixed in the x direction... etc. URx, URy, and URz are the rotations in the x, y and z directions. URx = 0 means the rotation was fixed in the x direction... etc.

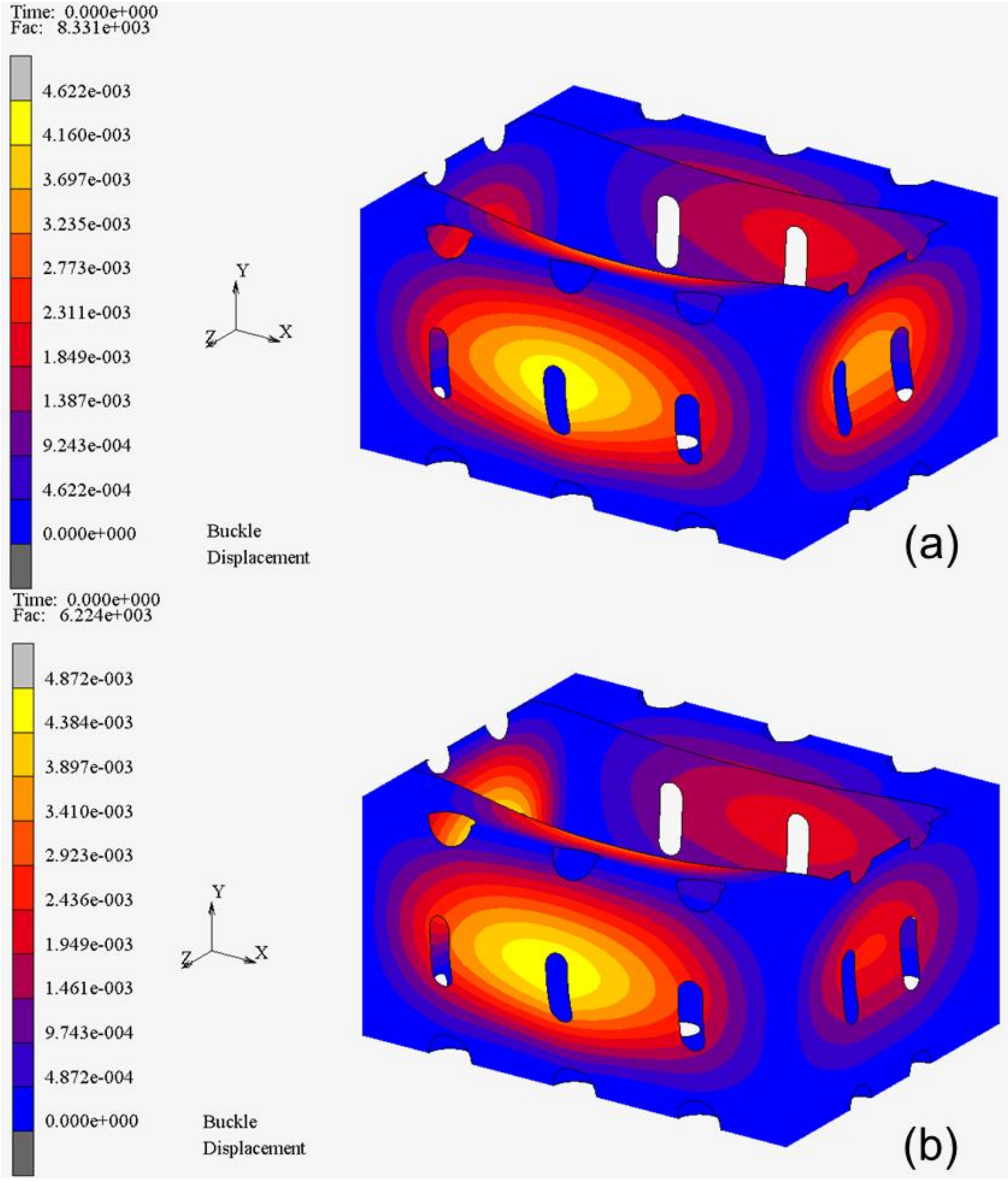

Fig. 7.8 Plot showing the first buckling mode (displacement) for the ‘Midvent’ carton design (a) at ambient conditions (23 ± 1 °C, 50% RH), and (b) at cold conditions (7 ± 1 °C, 92 ± 5% RH)

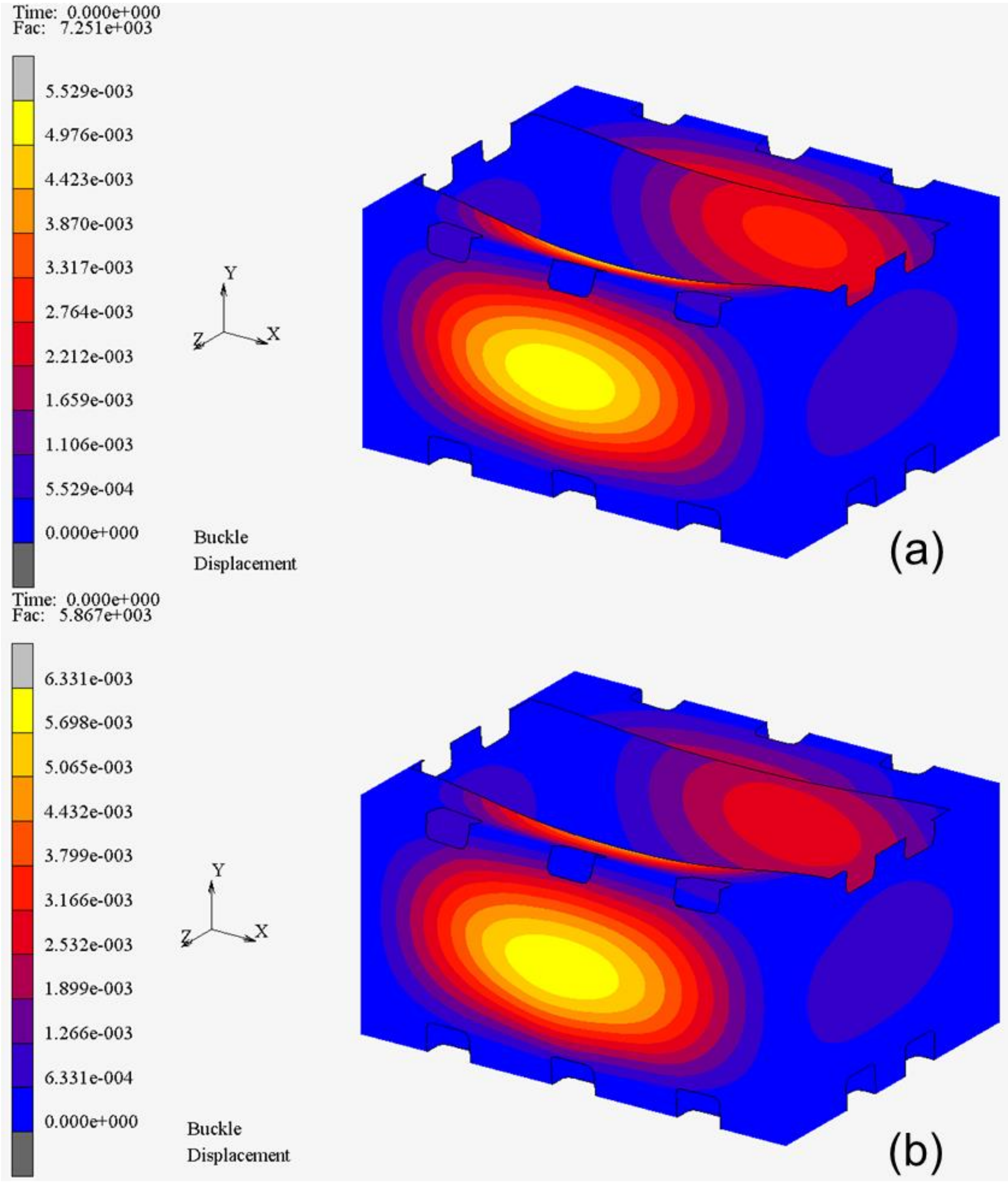

Fig. 7.9 Plot showing the first buckling mode (displacement) for the 'Edgevent' carton design (a) at ambient condition (23 ± 1 °C, 50% RH), and (b) at cold conditions (7 ± 1°C, 92 ± 5% RH)

7.5. New carton design logistics and sustainability

7.5.1. Material utilisation

7.5.1.1. Commercial design

Currently, one of the majorly used commercial cartons for export of South African fresh pomegranate fruit is the (0.395 × 0.295 × 0.118 m) single layer carton. This was the carton

'CT1' in the previous study by Mukama *et al*. (2017) and Ambaw *et al*. (2017). This will be referred to as 'Current' carton in this study (Fig. 7.10).

7.5.1.2. Ventilation characteristics

Similar to the 'Edgevent', the 'Current' carton has same ventilation pattern along the top and bottom of the long side, 3 vent-holes along the top and 3 along the bottom. On the short side, the 'Current' carton has only two top vents along its short side (Fig. 7.10). The vent size of the 'Edgevent' on the long and short sides are double the size (30 mm) of those on the 'Current' carton (15 mm) (Table 7.2). This alteration was intended to avoid total blockage of the lower vent-hole by the tray placed in the cartons. On the other hand, the 'Midvent' top and bottom vents are 20 mm high with additional oblong vents (20 × 40 mm). This was designed to include a direct central passage for the cooling air over fruit to improve cooling rates and uniformity. Table 7.2 describes the vent-hole characteristics of the studied carton designs. The ventilation, loading, and surface area of the studied cartons is shown in Table 7.3.

Table 7.2 Vent-hole characteristics on the long, short, and bottom faces of the studied cartons

Carton design	Orientation	Vent number	Vent shape	Vent dimensions (mm)
'Edgevent'	Long side	6	Rectangular*	40 × 30 (width × height)
	Short side	4	Rectangular*	40 × 30 (width × height)
	Bottom	6 5	Rectangular* Circular	40 × 10 (width × height) 25 (diameter)
'Midvent'	Long side	6 3	Semi-circular Oblong	40 × 20 (diameter × height) 20 × 40 (width × height)
	Short side	4 2	Semi-circular Oblong	25 × 10 (width × height) 20 × 40 (width × height)
	Bottom	6 5	Semi-circular Circular	40 × 10 (diameter × height) 25 (diameter)
'Current'	Long side	6	Semi-circular	40 × 15 (diameter × height)
	Short side	2	Semi-circular	30 × 15 (diameter × height)
	Bottom	5	Circular	25 (diameter)

*The rectangular vents had smooth curving corners

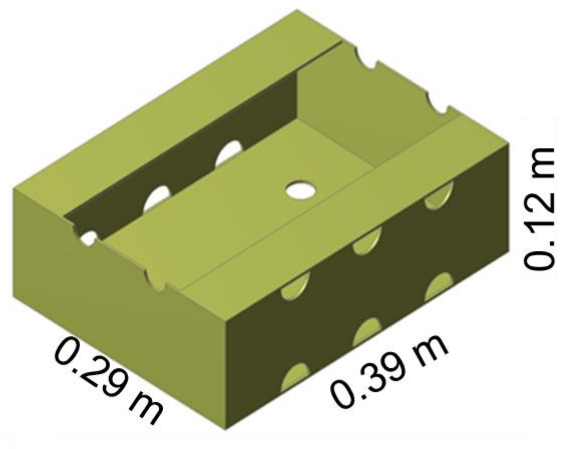

Fig. 7.10 Schematic showing commercial carton design ('Current' carton)

Considering that the new carton designs carry two layers of fruit, one carton can thus be equated to two 'Current' cartons in terms of fruit volume. Thus, the difference in corrugated fibreboard material required to manufacture the 'Current', 'Edgevent', and 'Midvent' cartons was calculated (Table 7.3). In comparison to two 'Current' cartons and for similar volume of fruit contained, the 'Edgevent' saved 0.184 m^2 of fibreboard material while the 'Midvent' saved 0.182 m^2. The small variation between the two new designs is due to difference in carton ventilation.

7.5.2. Throughput and shipping density

In terms of shipping density, fruit is exported in 40-ft (2.4 × 12 × 2.4 m) or '20 ft.' (2.4 × 6 × 2.4 m) refrigerated containers. These are normally loaded with pallets of cartons up to the red line, about 2.2 m high leaving space above for cooling air circulation (Getahun *et al.*, 2018). The 'Current' cartons are stacked 10 cartons per layer on a standard ISO2 pallet (1.2 × 1.0 m), 20 cartons high in a reefer (Table 7.3). Taking a 12-fruit count per carton, this implies that one pallet in the container holds 2,400 pomegranate fruit. The 'Edgevent' and 'Midvent' carton designs stacked 10 cartons per layer on the standard ISO pallet, 11 cartons high in a reefer. Taking a 24-fruit count per carton (12 fruit in each layer), one pallet in the reefer holds 2,640 pomegranate fruit (Table 7.3). This is an extra 240 fruit per pallet in the reefer in comparison to the 'Current' carton. Thus, in a reefer (40-ft) loaded to capacity with 20 pallets, the 'Edgevent' and 'Midvent' hold 4,800 more pomegranate fruit in comparison to the 'Current' carton.

In the 2018 season, South Africa exported 1,167,821 'Current' pomegranate cartons (POMASA, 2019). One reefer loaded with 20 pallets contains 4,000 'Current' cartons, therefore, if all fruit exported in South Africa in 2018 was by sea, 292 reefers (40-ft) were exported in the 2018 season. Given that a 'Current' carton pallet holds 2,400 fruit (taking a 12-fruit count), a reefer with 20 pallets will hold 48,000 pomegranate fruit equating to 14,016,000 pomegranate fruit exported in 2018. For the 'Edgevent' and 'Midvent' designs, a reefer with 20 pallets will contain 52,800 fruit. Thus, based on the number of fruit exported in 2018, the 'Edgevent' and 'Midvent' designs would export the fruit in 266 reefers. This is 26 reefers less than in the 'Current' carton.

The current world production of pomegranate is estimated at 3 million tons per year (Erkan & Dogan, 2018). With 'Current' carton, (assuming each carton is 4.5 kg) one reefer will hold approximately 18 tons of fruit. With 'Edgevent' and 'Midvent', (assuming each carton is 9 kg), one reefer will hold approximately 19.8 tons of fruit. Assuming all world fruit is transported by sea freight, this translates to over 166,667 reefers in the 'Current' carton and 151,515 reefers in the 'Edgevent' and 'Midvent' (15,152 less reefers).

7.5.3. Environmental sustainability

Recycling 1 ton of paper saves 15–17 mature trees (EPA, 2019). One tree makes about 152 corrugated fibreboard cartons of size 0.305 × 0.305 × 0.305 m (32 ECT C)—32 ECT is the Edge Crush Test (32 pounds per square inch), defining the stacking strength of the box, and C is the fluting (Packsize International, 2019). The 'Current' carton (0.395 × 0.295 × 0.105 m) and the 'Edgevent' and 'Midvent' (0.395 × 0.295 × 0.187 m) are double walled (BE flutes), we can thus assume that for the double walls, one tree will make half (76) the number of cartons. Thus, based on the total surface area of the cartons (Table 7.3), 1 tree will make 103 'Current' cartons and 80 'Edgevent' and 'Midvent' cartons. Given that a reefer holds 4,000 'Current' cartons and 2,200 'Edgevent' and 'Midvent' cartons, one reefer with 'Current' cartons will thus have an equivalent of 39 trees, while that with 'Edgevent' and 'Midvent' cartons will have 28 trees. Therefore, the new designs save approximately 11 trees per reefer.

Table 7.3 Studied cartons ventilation and loading

Carton	Orientation	Ventilation (%)	Fruit count/ carton	Carton layout on pallet	Carton layers/ pallet in reefer	No. of cartons/pallet stack	Number of fruit/pallet in reefer	Fiberboard total surface area (m^2) per carton
'Current'	Long side	7.9	12	2 × 3 + 1 × 4	20	200	2400	0.295
	Short side	7.3						
	Bottom	3.8						
'Edgevent'	Long side	9.7	24	2 × 3 + 1 × 4	11	110	2640	0.406
	Short side	8.7						
	Bottom	4.2						
'Midvent'	Long side	9.7	24	2 × 3 + 1 × 4	11	110	2640	0.408
	Short side	4.9						
	Bottom	4.2						

7.6. Conclusion

By running a virtual test, which took only few hours, it was possible to find an accurate measure of design parameters and detailed visualization of airflow contour and streamlines. These capabilities enable researchers in the postharvest area to analyse, characterize and compare alternative package designs and process evaluation, virtually. This saves time and money (i) in the early stage of the concept when designing cartons, and (ii) when producing the cartons by optimising the dimensions, volume, and the material cost of corrugated fibreboard carton manufacturing. The virtual approach also enables an explorative out-of-the-box thinking. Two new dual layer pomegranate fruit cartons were designed. In a fully loaded 40-ft reefer, the new designs hold up to 1.8 tonnes more fruit compared to the 'Current' export carton. Additionally, the new designs facilitate better airflow and have the required carton stacking strength under cold conditions. The 'Midvent' carton design generally performed best in mechanical strength requirements. The new carton designs can thus be commercialised to increase shipping density, reduce costs through increased volumes, and use less fibreboard material per unit volume of pomegranate fruit exported. This directly translates to saving the climate through reduced use of fibreboard materials, thus trees, given that the recycling chain may not capture 100% of the fibreboard material in the fruit supply chain.

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Chapter 8

Integration of virtual and physical testing in packaging for better space usage and increased throughput in the cold chain management of pomegranate fruit: Part 2, physical prototyping and testing

Abstract

The ease of sale of produce and customer satisfaction depends largely on the physical, textural, and chemical attributes of a given produce which impact on overall acceptability. In this study, the cooling and mechanical performance of two new cartons designed in part 1 ('Edgevent' and 'Midvent') was assessed. Additionally, some physical, and chemical quality attributes of pomegranate fruit precooled and cold stored in new design (ND), the 'Midvent', was monitored over a 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% relative humidity (RH)) and an additional 2 weeks at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH). These were compared with attributes of fruit stored in commercial design (CD). The 'Midvent' cooled pomegranate fruit 1 hour faster compared to the 'Edgevent' and commercial design. The 1.0 m pallet orientation recorded the lowest pressure drop in both new designs and is the most ideal for forced air cooling processes. Cooling heterogeneity was highest in fruit cooled in liners with 6.7 h difference between fruit at front and back of air inlet compared to 2.5 h in no-liner. Cold storage conditions caused over 20% loss in carton compression strength. The 'Edgevent' and 'Midvent' were 1.3% and 15.2%, respectively, above minimum stacking force requirement after 4 weeks under cold storage (7 ± 1°C, 92 ± 5% RH). In the fruit storage quality analysis, fruit respiration followed a similar pattern in ND and CD marked by a 64% reduction after precooling and average of 5.66 ± 1.23 mL CO2 l^{-1} kg^{-1} h^{-1} throughout the cold storage period. Fruit lost weight by 5.7% and 8.9% in the ND and CD, respectively, at the end of the shelf life period. The average decay incidence in both carton designs was 4.5% of the stored fruit at the end of the storage period and fruit colour was generally stable with relatively constant hue angle throughout the storage period. Fruit in new and commercial carton designs scored high on desirable sensory attributes at the end of the overall storage period. Therefore, the new carton design preserves commercial quality of pomegranate fruit.

8.1. Introduction

Fruit perishability depends largely on the type of fruit and postharvest handling conditions. High respiration rates in climacteric fruit, dehydration, oxidation and microbial decay are some of the major challenges facing the horticultural industry, affecting the supply of raw and fresh-cut fruits, that are otherwise, on an ever-increasing demand (Ladaniya, 2008; Robertson, 2010; Aindongo *et al*., 2014). Optimal packaging and cold chain maintenance are critical postharvest operations to minimize losses and wastage. Proper cold chain operations begin with harvesting fruit at the coldest times of the day, followed by precooling, with intent to rapidly remove field heat after harvest (Berry *et al*., 2017). Precooling minimizes physical and biological changes of harvested produce during postharvest handling (Ravindra & Goswami, 2008). Once the produce attains the storage temperature, it is stored in cold rooms or reefers in transit. Finally, produce should be handled at recommended temperature during display at a warehouse or retail stores, as well as in consumer households.

Pomegranates exhibit a non-climacteric respiration pattern: ripening process stops once the fruit is detached from the parent plant (Kader, 2006), however, they produce carbon dioxide and ethylene at incremental rates with temperature increase (Elyatem & Kader, 1984). There is a growing trend in the use of pomegranates as an ingredient in food, cosmetic, and pharmaceutical industries given their bright red colour, sweet-sour flavour, and nutraceutical properties (Fawole & Opara, 2014). However, pomegranates are vulnerable to moisture loss, fungal infections, bruising and decay if the fruit is not properly handled, packaged, and stored after harvest (Kader, 2006; Caleb *et al*., 2012; Munhuweyi *et al*., 2016). Pomegranates can be kept up to 4 months if fruit is kept at temperature and relative humidity (RH) between 5 °C to 7 °C and 90% to 95%, respectively. Rapid loss of moisture and the associated shrivelling is one of the most common challenges after harvest in cases of temperature abuse (Fawole & Opara, 2013; Arendse *et al*., 2014; Mukama *et al*., 2019).

Packages play a key role in preserving the quality of fruit. The most important is the protection of fruit against mechanical damage from compressional forces and external shocks. Mechanical and structural integrity is one of the critical design features for packages for use in the fruit industry (Pathare *et al*., 2012). This is in consideration of the handling chain where cartons have to be stacked onto each other and held in conditions of low temperature high humidity. In addition to mechanical protection, packaging is also applied to minimise loss of produce moisture. For example, in the pomegranate industry, the fruit are packaged in polyliner bags that minimise moisture loss from these fruit by creating a moisture saturated environment around the fruit that minimises further loss of moisture from the fruit (O' Sullivan *et al*., 2016; Mukama *et al*., 2019). Polyliner bags also protect packaged fruit from pathogens in the air and modify the levels of O_2/CO_2 in the bag atmosphere meant to further slowdown metabolic processes (Berry *et al*., 2015; Mphalele *et al*., 2016). The limitation with liner packaging is that in case of temperature fluctuations, the moisture could condense on the fruit creating damp conditions that could promote fungal growth and proliferation on fruit surfaces, hence decay (Ngcobo *et al*., 2013). The polyliners also increase produce cooling time during precooling (Mukama *et al*., 2017).

In keeping fruit quality, packages are designed to enable fast and uniform cooling of fruit (Berry *et al*., 2016, 2017; Getahun, 2017a, b; Mukama *et al*., 2017). This is achieved through proper design of vent-holes on the carton such that cold air easily streams through fruit stacks within a reefer and cold room and during the forced air-cooling process. That way, the deteriorative physiological process of the fruit are slowed down, extending the fruit shelf life and keeping fruit quality. Package design and evaluation should employ a multiparameter approach giving a holistic assessment of all functionalities and parameters to help avoid contradictions in the design requirements. For example, increasing the ventilation area to improve cooling rates without consideration of the carton strength may result in a carton lacking in mechanical integrity, increasing chances of fruit mechanical damage.

In part 1 of this study (Chapter 7), we virtually designed new ventilated double fruit layer corrugated paperboard cartons, 'Edgevent' and 'Midvent'. Following a multiparameter performance analysis approach, in this part of the study, the prototypes were manufactured and tested on cooling characteristics and mechanical performance. Additionally, the quality of pomegranate fruit precooled and stored in the 'Midvent' was monitored over 12 weeks under cold storage (7 ± 1 °C, 95 ± 2% RH), plus additional 2 weeks at ambient conditions (20 ± 2 °C; 65 ± 5% RH). Parameters investigated include weight loss, fruit respiration, fruit colour changes, decay incidence, and changes in Total Soluble Solids. The fruit quality was compared with those of fruit packaged in the most widely used commercial carton design.

8.2. Manufacture of prototypes

The two new carton designs were manufactured at APL cartons, Worcester, Western Cape, South Africa, from corrugated paperboards with two flutings (B and E) and three liners: 175K/150B/175K/150E/175K (150B and 150E are the flutings and the 3 × 175K are the liners).

The K stands for kraft (paper type) and the figures are the grammage (g m^{-1}) of the paper. The designed cartons were cut using a large-format computer controlled flatbed cutter (Aristomat TL 1625, Aristo cutting solutions, Hamburg, Germany). The carton cuts were then manually folded and glued (Fig. 8.1).

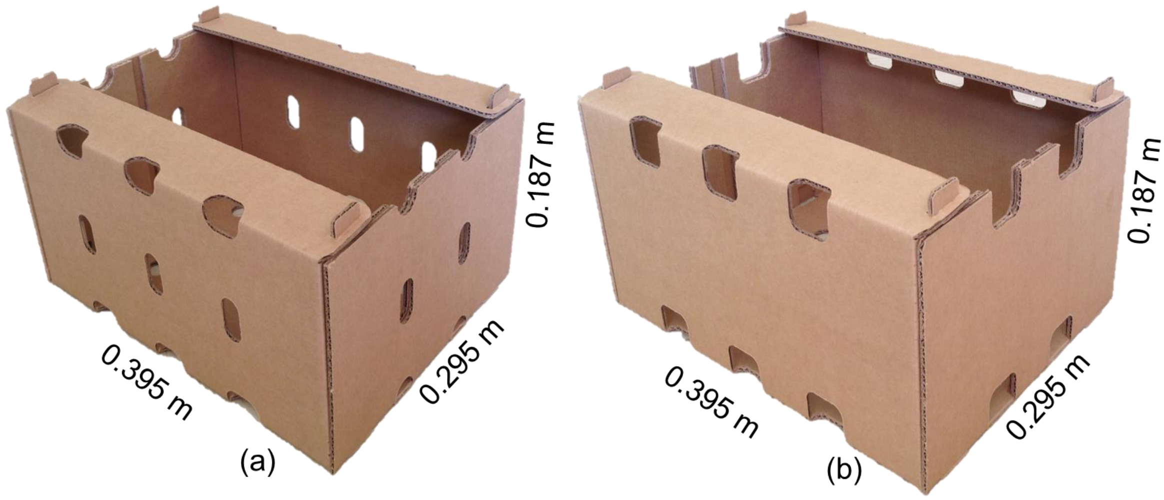


Fig. 8.1 Photograph of the manufactured new carton designs (a) 'Midvent' and (b) 'Edgevent'

8.3. Testing airflow and cooling performance

8.3.1. Fruit sample preparation

Pomegranate fruit (cv. Wonderful) was obtained at commercial maturity from Sonlia Pack-house (33°34’851”S, 19°00’360”E), Western Cape, South Africa and transported to Stellenbosch University Postharvest Technology Research Lab. The fruit were then packaged into the manufactured ‘Edgevent’ and ‘Midvent’ cartons and conditioned to room temperature for subsequent experimental treatments. The packaging procedure for pomegranate fruit in the manufactured cartons included: (i) fruit in polyliner (liner); and (ii) fruit in no liner. In both cases the fruit were packed onto two trays separated by two foam sheets (Fig. 8.2) to provide mechanical protection against abrasion and bruising during handling.

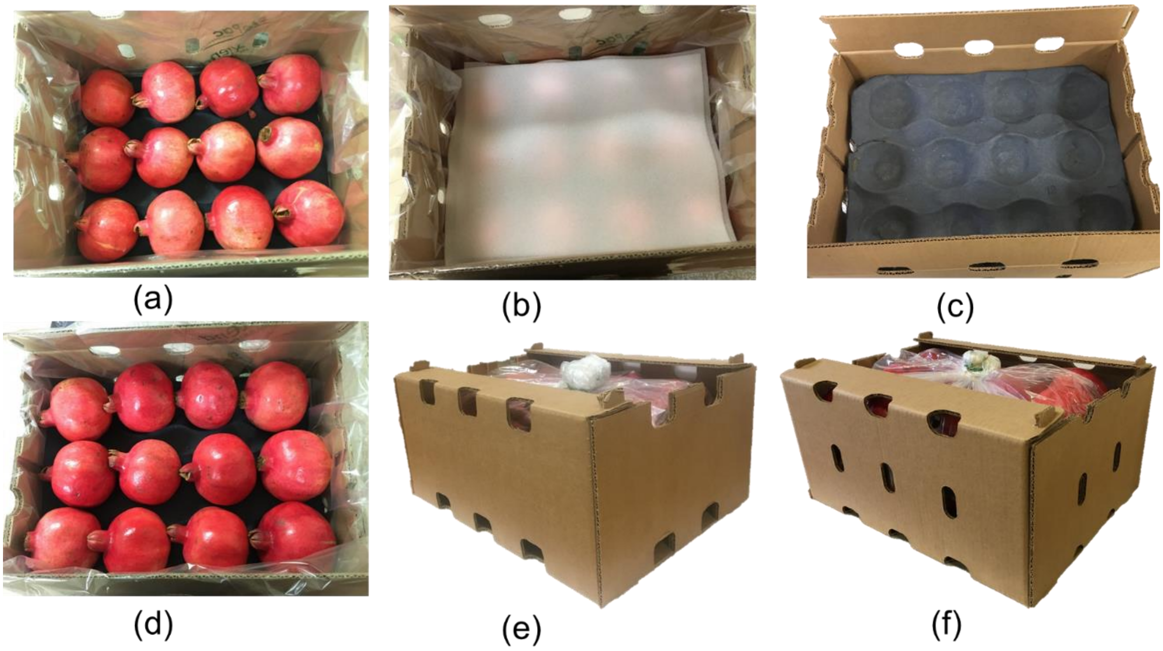


Fig. 8.2 Components of pomegranate fruit packaging in the new carton designs: (a) the bottom layer of fruit on a tray in carton with liner, (b) two 3 mm foam sheets on top of first layer of fruit, (c) top tray on top of foam sheet (d) second layer of pomegranate fruit on top tray (e) the 'Edgevent' design with liner packaged pomegranate fruit, and (f) the 'Midvent' design with liner packaged pomegranate fruit

8.3.2. Experimental measurements

8.3.2.1. Pressure drop in forced air cooling (FAC) process

The pressure drop was measured based on the method described by Mukama *et al*. (2017). However, in this experimental study, only one layer of cartons was used (Fig. 8.3 (a)). The cartons were stacked on a standard pallet (1.2 × 1.0 m). Pressure drop measurements were made for the layer of empty cartons, layer of cartons with fruit without liner, and layer of cartons with fruit within liner. Centrifugal fan (Kruger KDD 10/10 750W 4P-1 3SY) of the FAC system drew air through the air inlet face (1.2 m side of pallet) of the layer of cartons. For the empty cartons, air was also drawn from the 1.0 m side of the pallet to determine the effect of the pallet orientation to airflow. All other air inlets except the test orientation were sealed with plastic (Fig. 8.3 (a)). Pressure drop was monitored using differential pressure meter (Air Flow Meter Type A2G-25/air2guide, Wika, Lawrenceville GA 30043, USA with a long-term stability of ± 1 Pa) with data controller (WCS-13A, Shinko Technos CO LTD, Osaka, Japan). Velocity measurements were done using (Alnor velometer AVM440, TSI Incorporated, Shoreview MN 55126, USA).

8.3.2.2. Fruit cooling characteristics

The cartons were stacked in one layer containing 10 cartons on a pallet stack (Fig. 8.3 (b)) assembled with a forced air cooling system in a cold storage room. This was set up as described by Mukama *et al*. (2017). A single layer of cartons was used in this study because the study by Mukama *et al*. (2017) found more cooling heterogeneity between boxes in a layer than between carton stack layers. In each carton, the centre fruit in each layer was data logged (Fig. 8.3 (b)) with T-type thermocouples (Thermocouple products Ltd, Edenvale, South Africa, with operating range of -30 to 100 °C and accuracy of ± 0.025%) placed at the fruit's thermo-centre recording temperature data at 5 minute intervals. Temperature data for each carton is an average of two data logged fruit in the two layers. The cooling airflow rate was maintained at 0.5 l s^{-1} kg^{-1} and temperature 7 °C. Temperature at different locations in the cooling room was monitored by Tinytag sensors (Tinytag TV-4500, Hastings Data Loggers, Australia). The cooling room had three 30 cm diameter evaporator fans with a capacity of 1290 m^3 h^{-1} connected to a finned tube heat exchanger cooling unit (1.25 × 0.40 × 0.36 m) and compressor unit (CR36K6-TF6-121 model, Emerson Climate Technologies). Cooling was monitored for fruit in liner and no-liner packaging.

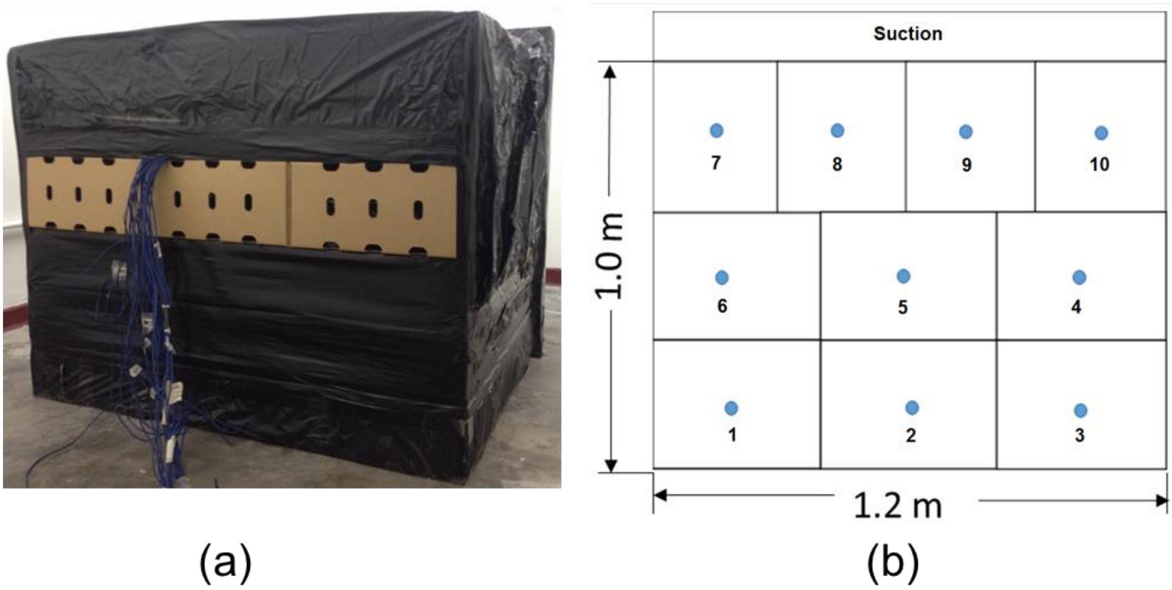


Fig. 8.3 Schematic showing (a) set up for measurement of resistance to airflow and forced air cooling rates, (b) layout of cartons on pallet and position of data logged sample fruit

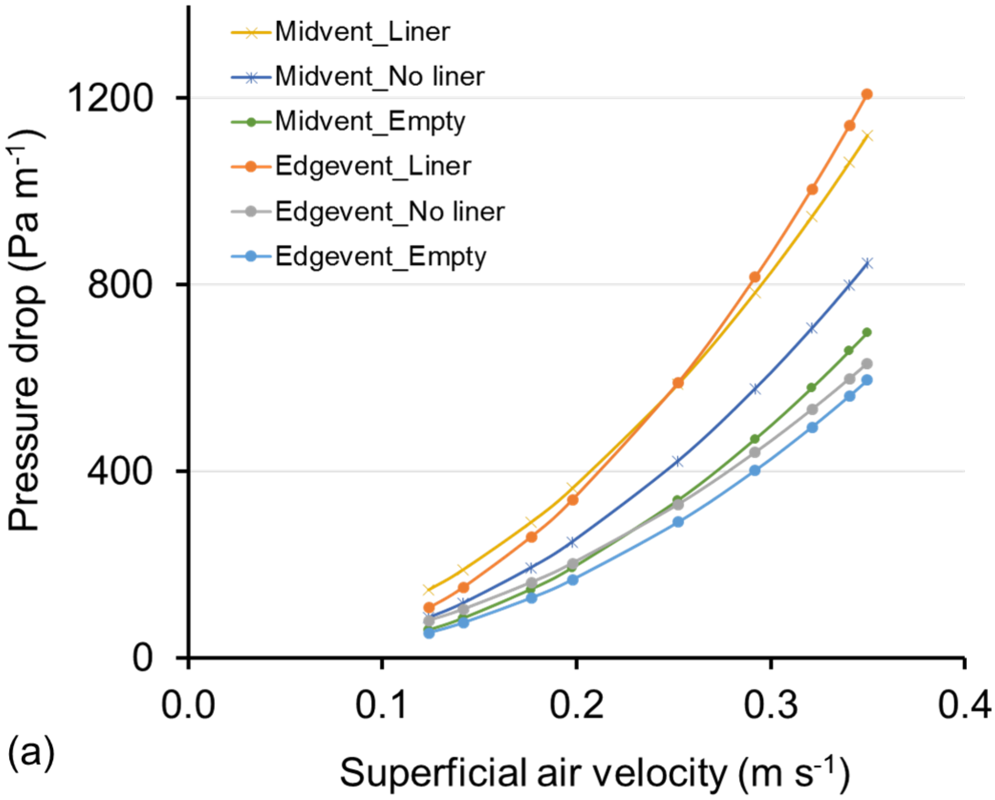
8.3.3. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 13 (StatSoft, Inc. Oklahoma, USA). Means were separated using Duncan's multiple range tests (Factors: carton design and lining).

8.3.4. Effect of carton design on pressure drop

The pressure drop of the air flowing through a stack of cartons is due to airflow resistance by the cartons and their components. As expected, empty cartons had the least resistance while the cartons with fruit in liner had the highest airflow resistance in both carton designs (Fig. 8.4 (a)). The pressure drop was generally similar for both carton designs, although the 'Edgevent' generally had slightly lower resistance to airflow compared to the 'Midvent'. For example, at superficial air velocity 0.2 m s^{-1}, the pressure drop was 200 and 240 Pa m^{-1} for no liner packaging in the 'Edgevent' and 'Midvent', respectively. This could imply that more air flows through the top-bottom vents, probably taking the easiest route at the bottom below the tray and top where the carton components may have not occupied, contrary to the 'Midvent' with top-bottom vents almost half the size that of the 'Edgevent'. Similar to observations by Mukama *et al*. (2017) and Ambaw *et al*. (2017) for the 'Current' carton, cartons with liner presented the highest pressure drop, followed by cartons with no liner, then the empty cartons.

Based on results from pressure drop comparison of the 1.0 m and the 1.2 m orientations of the pallet stacks (Fig. 8.4 (b)), the 1.0 m orientation recorded a lower pressure drop compared to 1.2 m in both carton designs. The 'Edgevent' also records comparatively lower pressure drops. For example, at superficial air velocity 0.2 m s^{-1}, pallet orientation 1.0 m had pressure drop at about 120 and 150 Pa m^{-1} for the 'Edgevent' and 'Midvent', respectively. The 1.2 m pallet orientation had pressure drop 170 and 200 Pa m^{-1} for 'Edgevent' and 'Midvent', respectively (Fig. 8.4 (b)). This was due to a more even vent-hole alignment in the 1.0 m orientation, making it the most ideal orientation for forced airflow cooling processes.



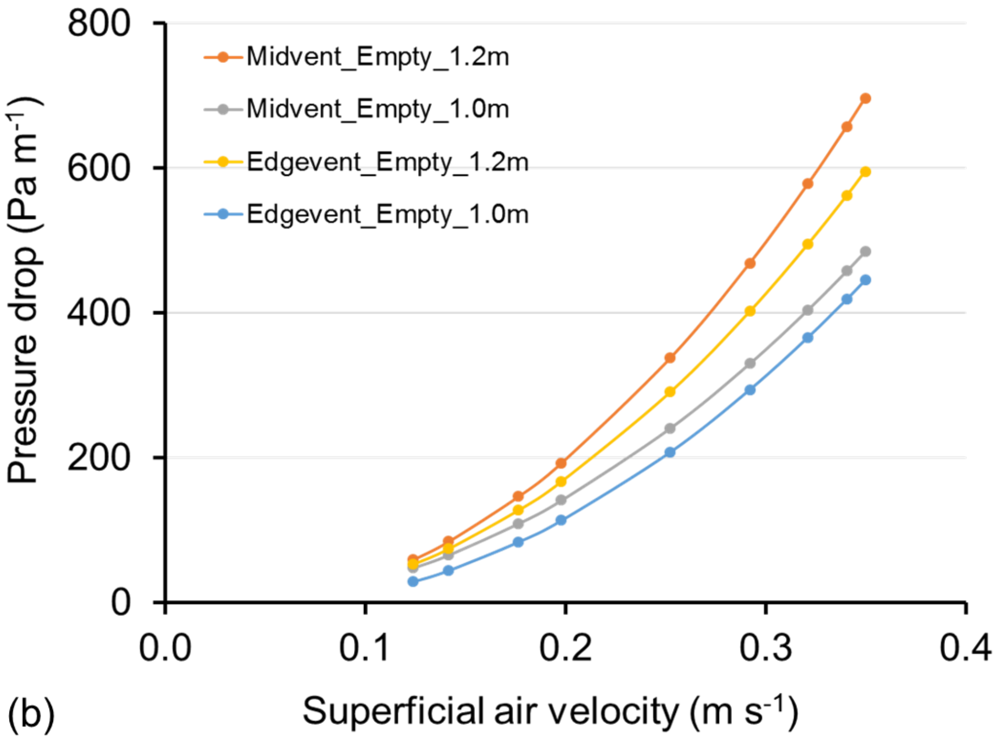


Fig. 8.4 Pressure drop across a single carton layer as a function of airflow rates through the layer of (a) 1.2 m pallet orientation of 'Edgevent' and 'Midvent' carton designs: empty, in polyliner, and in no liner packaging, (b) 1.0 m and 1.2 m pallet orientation of empty 'Edgevent' and 'Midvent' carton designs

8.3.5. Fruit cooling rate and uniformity

8.3.5.1. Fruit cooling rate

The fruit cooling rates were indicated by the seven eighth cooling time (SECT) in Table 8.1. Generally, the 'Midvent' cooled pomegranate fruit faster in comparison to the 'Edgevent' carton. Fruit in liner in the study on commercial carton ('CT1') by Mukama *et al*. (2017) took over 12 hours to cool, while the 'Edgevent' and 'Midvent' took 13.1 and 12.6 hours respectively. In no liner packaging, the fruit in commercial carton required 4.5 hours to cool while the 'Edgevent' and 'Midvent' required 4.4 and 3.5 hours respectively. This means that the added middle vent-holes in the 'Midvent' carton facilitate better exchange of heat between the fruit and the cooling air. However, the seven-eighths cooling time difference between the 'Edgevent' and the 'Midvent' was only significant for the fruit cooled without liner (Table 8.1). This may show that even with improved ventilation of the 'Midvent', the cooling rates in liner packaged fruit are influenced most by the barrier properties of the plastic lining to heat exchange. Liners act as barriers reducing the energy transfer between the fruit and its surroundings, increasing the cooling times (O'Sullivan *et al*., 2016, 2017; Ambaw *et al*., 2017; Mukama *et al*., 2017). Ambaw *et al*. (2017) found a 74% reduction in convective heat transfer coefficient during forced air cooling of pomegranate fruit in liner compared to no-liner.

Table 8.1 Seven eighth cooling time (SECT) of pomegranate fruit in liner and no liner packaging modes in the 'Edgevent' and 'Midvent' carton designs. Different letters in same column indicate significance difference (p = 0.00016). Cooling was done at constant airflow rate of 0.5 l kg-1 s-1 at 7 °C

Carton design	**Packaging mode**	
	Liner packaging	No liner packaging
Midvent	12.6^{a}	4.4^{a}
Edgevent	13.1^{a}	3.5^{b}

8.3.5.2. Cooling uniformity

In terms of variability of fruit cooling within the layer of fruit, the trend was similar in both carton designs. Similar to observations made by Ambaw *et al*. (2017) and Mukama *et al*. (2017) for fruit packed in the studied commercial carton, fruit upwind in the set up cooled faster, and the trend of cooling time significantly increased further from the point of cooling air entrance (Fig. 8.5). The heterogeneity was however more prominent in liner packaged fruit, with significant differences in seven eighths cooling time among the front, middle and back rows.

Average SECT at the front was 9.2 hours, 12.3 hours middle, and 15.9 hours at the back. This temperature variation front to back is in relation to the reduction in cooling ability of the circulating air having already picked heat from fruit upwind. In no liner packaged fruit, the difference in SECT (2.5 hours) was smaller ranging from 2.6 hours at the front to 5.1 hours at the back (Fig. 8.5). This is a smaller variation than observed in the commercial carton of 2.6 hours to 6.1 hours at front to back fruit (3.5 hours) (Mukama *et al*., 2017).

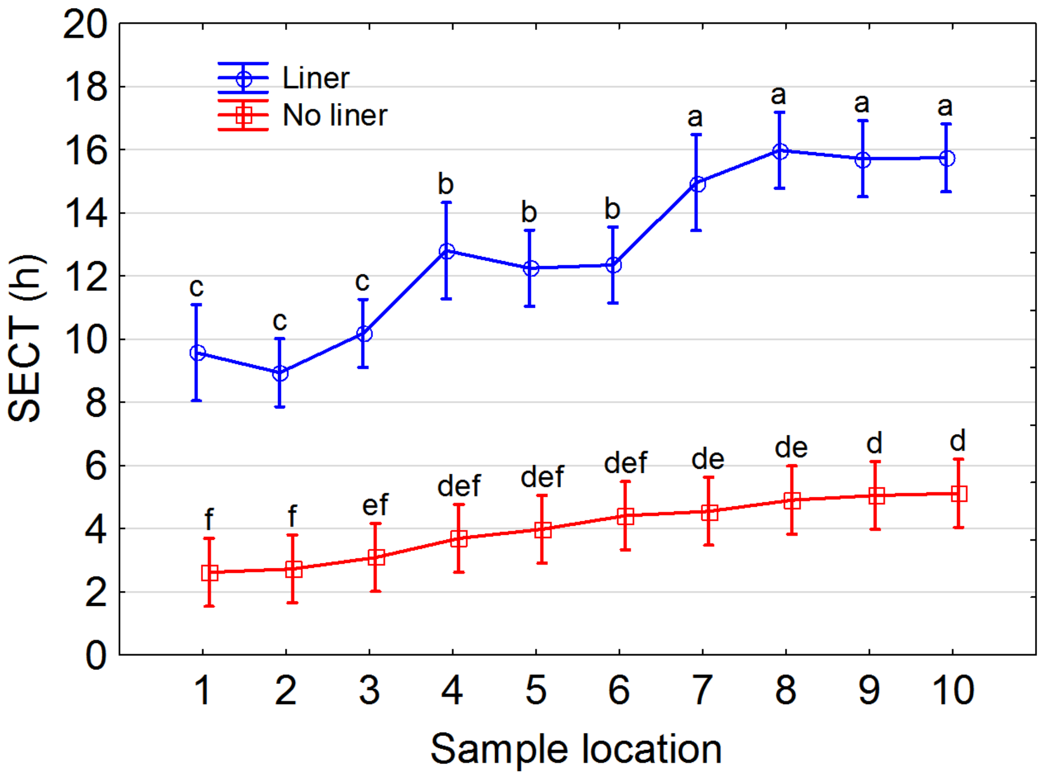


Fig. 8.5 Seven eighth cooling time (SECT) of pomegranate fruit per sample location in liner and without liner in the 'Midvent'. Verticle bars denote 0.95 confidence intervals of 3 replicates. Different letters indicate significance difference (p = 0.00211). Cooling was done at constant airflow rate of 0.5 l kg^{-1} s^{-1} at 7 °C

8.4. Compression tests

8.4.1. Experimental box compression test

The strength of the 'Edgevent' and 'Midvent' cartons was measured using the box compression test (BCT), in accordance with the ASTM D642 standard (ASTM, 2010). The cartons were preconditioned at 30 ± 1 °C, 25 ± 5% Relative humidity (RH) for 24 hours and then 23 ± 1 °C, 50% RH for 24 hours as recommended by ASTM D4332 standard (ASTM, 2006). Carton preconditioning was carried out in a versatile environment chamber. Each carton was then compressed by a continuous motion platen moving at a speed of 12.7 ± 2.5 mm min^{-1} until failure. The fixed-platen method of compression testing was used using box compression tester

(M500-25CT, Testomatic, Rochdale, UK) (Fig. 8.6). A preload of 222 N was applied on the test cartons to remove initial transient effects. To determine the effect of cold storage on the carton strength, another set of cartons (i) empty, and (ii) with fruit, were also preconditioned at 7 ± 1 °C, 92 ± 5% RH for 24 hours and then compressed as described above. Additionally, to simulate fruit shipping period under refrigeration, the cartons (empty) were stored at 7 ± 1 °C, 92 ± 5% RH for 4 weeks, and box compression tests were done. Experiments were done in triplicates for both carton designs.

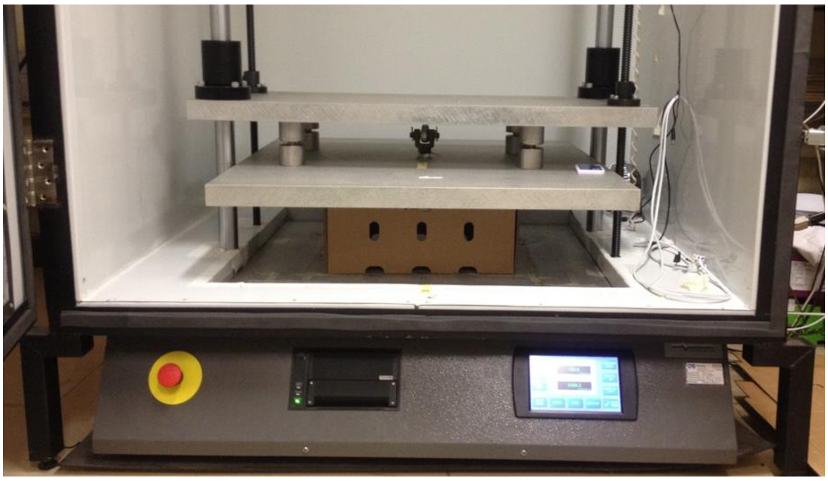


Fig. 8.6 Compression testing of the cartons with box compression tester

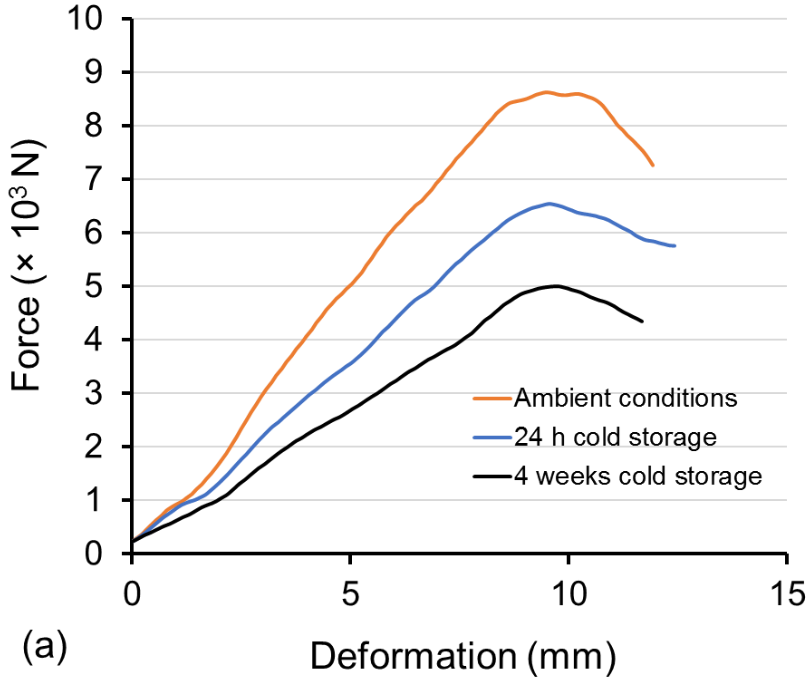
8.4.2. Compression results

The experimental box compression test results of the 'Midvent' and 'Edgevent' are shown in Fig. (8.7 (a)) and Fig. (8.7 (b)), respectively. The 'Midvent' is generally a stronger carton design compared to the 'Edgevent'. At normal room conditions, the 'Midvent' can withstand a stacking (compression) force of 8954.6 N while the 'Edgevent' withstands 7124.4 N. The 'Current' carton has a maximum stacking force of 8948.9 N. At cold storage conditions, both carton designs lose strength to 6744.2 N and 5711.1 N for the 'Midvent' and 'Edgevent', respectively (Fig. 8.7). The over 22% loss in strength may be attributed to the absorption of moisture under cold storage (7 ± 1 °C, 92 ± 5% RH) by the paperboard material that could break cellulose fibre bonds weakening the paperboard material. Zhang *et al*. (2011) reported 18.9% reduction in the edge compressive strength of cardboard when the relative humidity of the storage room was increased gradually from 30–90%. Given that the minimum compression force requirement of the designs is 4500 N, the carton designs, the 'Edgevent' and 'Midvent' are thus 26.9% and 49.9% above minimum stacking force requirement, respectively, at cold conditions. Fig. (8.8) shows the visual deformation of the compressed cartons. Deformation mainly occurred on the long sides of the carton with minimal deformation along the bottom of the short side. This is because the short side was double walled which gives it more resistance to compressive forces. The design of the short side with double walls is thus necessary to achieve the required mechanical integrity of the cartons. Physical observation (Fig. 8.8) also shows that the 'Midvent' and 'Edgevent' collapse about 30 mm from the top and bottom edges along the long side. This could be the reason why the 'Edgevent' is a weaker carton compared to the 'Midvent' because at that point is the top end of the "Edgevent' vents that became the line of weakness. Given that commercial cold storage cartons are manufactured from paper grammage 200 g m^{-1} (Grobbelaar, D, 2018, Structural designer, APL Cartons, Worcester, South Africa, Personal communication, 20 September), the commercial cartons would be much stronger than the test cartons in this study.

Comparing the numerical predictions in Chapter 7 section 7.4.2 with the box compression test results here, the numerical predictions of the carton strength agree reasonably well with the experimental results and were within a difference of about 10%. The buckling load or the compression strength for the 'Midvent' carton was 8089 N at ambient condition and 6085 N at cold conditions. In comparison with the experimental compression strength, at ambient condition, there was a percentage difference of 10.7%. Similarly, at cold condition, the percentage difference was 10.8%. For the 'Edgevent' carton, the compression strength obtained from the FEA simulation at ambient condition was 7263 N and differed by 1.9% when compared with the experimental compression strength. At cold conditions, the compression strength obtained from the FEA model was 5891 N; a 3.1% difference between the numerical and experimental compression strength.

After 4 weeks under cold storage, the 'Midvent' maximum compression force was 5185.2 N, while 'Edgevent' withstood a maximum force of 4556.9 N (Fig. 8.7). This translates to 23.1% and 20.2% further loss in carton strength for the 'Midvent' and 'Edgevent', respectively, after 4 weeks compared to after 24 hours under cold storage. However, both cartons are still above estimated minimum stacking force requirement after 4 weeks under cold storage. In spite of the significant changes on maximum compression force, moisture absorption under the refrigeration conditions did not have much effect on the deformation of the compressed cartons. For example, for Midvent, deformation at ambient condition, after 24 hour cold storage, and after 4 weeks cold storage was 10.0 ± 0.5 mm, 9.6 ± 0.1 mm and 9.9 ± 0.7 mm, respectively (Fig. 8.7).

The compression force vs deformation of cartons loaded with fruit (Fig. 8.9) can be divided into two sections, the first section (a–b) represents the maximum force at which failure of the carton occurs. The second section (b–c) represents the maximum compression force at which the fruit fail (the fruit are crushed). Fruit were crushed at force above 20,000 N. This is over 3-fold the compression force of the empty cartons. At the maximum compression force, all fruit were crushed open (Fig. 8.10).



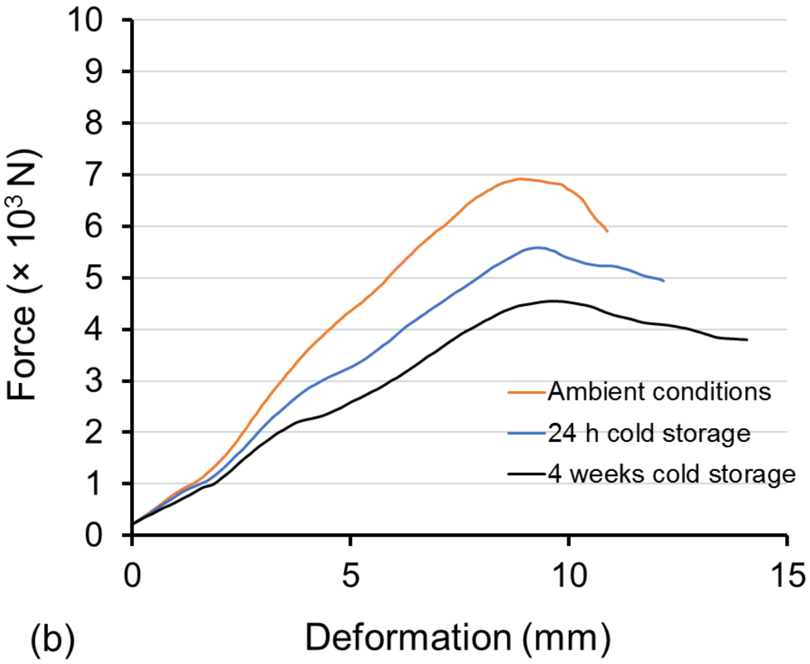


Fig. 8.7 Force vs deformation of the (a) 'Midvent' and (b) 'Edgevent' at ambient conditions (23 ± 1 °C, 50% RH), under cold storage conditions (7 ± 1 °C, 92 ± 5% RH), and after 4 weeks under cold storage

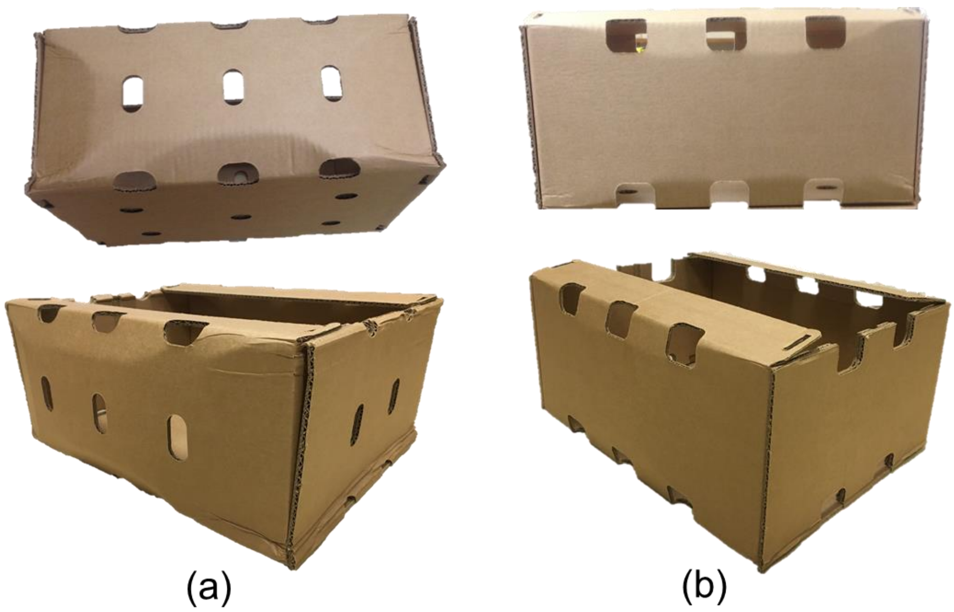


Fig. 8.8 Deformation of (a) 'Midvent' and (b) 'Edgevent' cartons compressed using box compression tester

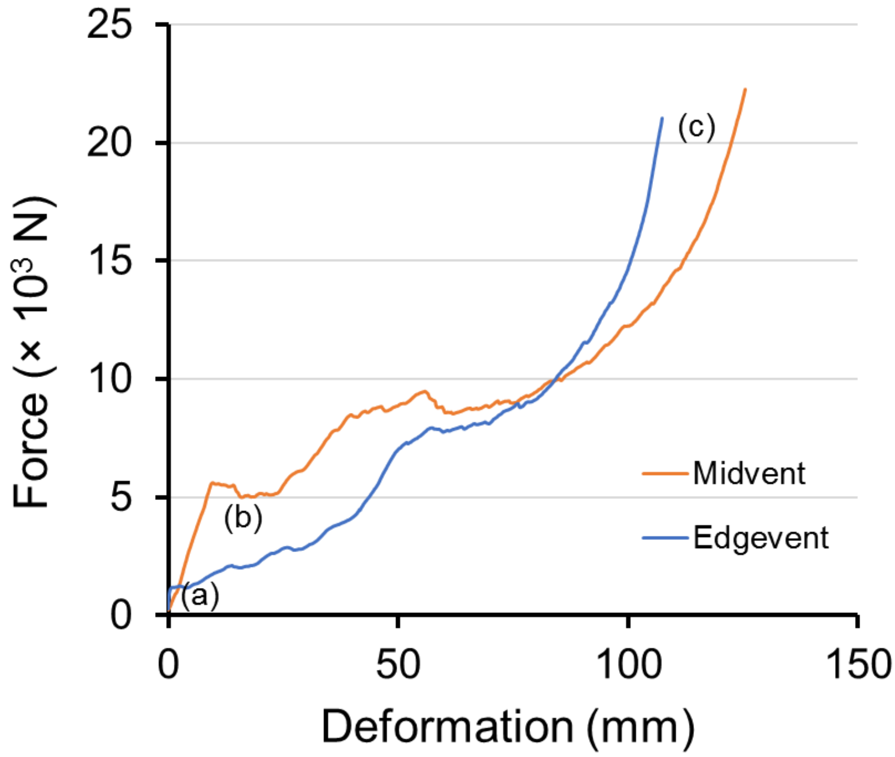


Fig. 8.9 Force vs deformation of the 'Midvent' and 'Edgevent' with pomegranate fruit after 24 hours under cold storage conditions (7 ± 1 °C, 92 ± 2% RH)

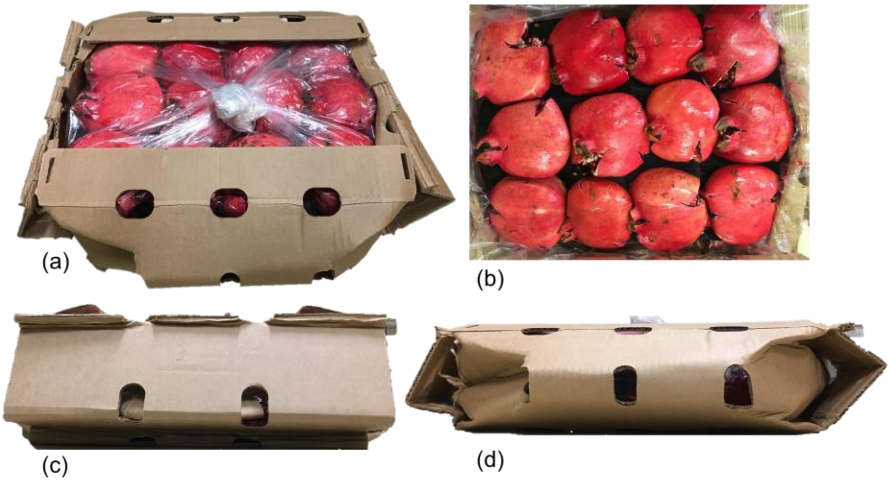


Fig. 8.10 Crushed fruit and carton following box compression test after 24 hours under cold storage (7 ± 1 °C, 92 ± 5% RH) (a) compressed carton and fruit in liner, (b) crushed fruit, (c) short side of carton, and (d) long side of new carton design

8.5. Analysis of quality of fruit in the new carton design

8.5.1. Fruit sample preparation and packaging

Fresh pomegranate fruit (cv. Herskowitz) were obtained at commercial maturity from Sonlia Pack-house (33°34'851"S, 19°00'360"E), Western Cape, South Africa and transported to Stellenbosch University Postharvest Technology Research Lab. The fruit were procured and transported in the commercial carton design (CD) (Fig. 8.11 (a)). The cartons were divided into two groups of 30 each and the second group was repackaged in the new carton design (ND) (Fig. 8.11 (b)).

The commercial carton (0.395 × 0.295 × 0.104 m) had a large rectangular vent-hole on the long side located at the top of the carton (Fig. 8.11 (a)). The new design (ND) was the 'Midvent' (Fig. 8.11 (b)) (0.395 × 0.295 × 0.187 m), the best performing carton in terms of strength and fruit cooling. The cartons were packed with pomegranate fruit on trays enveloped in single non-perforated 10 µm thick high density polyethylene (HDPE) plastic film liner (Fig. 8.11). The CD had one layer of 12 fruit, gross weight 3.8 ± 0.3 kg while the ND had two fruit layers, gross weight 8.3 ± 0.3 kg. Fruit were equilibrated to room temperature (20 ± 2 °C 65 ± 5% RH) in anticipation for the treatments. Tiny Tag TV-4500 data loggers (Gemini Data Logger, Sussex, UK) were used to monitor and record the temperature and RH in the environments.

Fig. 8.11 Photograph of (a) commercial carton design (CD), and (b) new design (ND) with fruit in polyliner

8.5.2. Experimental procedure

8.5.2.1. Forced air cooling and cold storage

Pomegranate fruit in CD and ND was precooled using forced air cooling method described in section 8.3.2.1. Precooled fruit were then kept in the same cold storage room after precooling for further 12 weeks. Temperature and relative humidity in the cold room was kept at 7 ± 1 °C; 90 ± 2%. After 12 weeks under cold storage, the pomegranate fruit cartons were further stored under ambient conditions (20 ± 2 °C, 65 ± 5% RH) for 2 weeks to simulate shelf storage and open market conditions. Table 8.2 summarises the measurements that were done to assess the fruit quality over the cold storage period at 2 weeks intervals, and at the end of the 2 weeks ambient storage period in the CD and ND cartons.

Table 8.2 Measurements taken to assess fruit quality over the 12 weeks cold storage period (7 ± 1 °C; 90 ± 2%) and at the end of the 2 weeks ambient storage period (20 ± 2 °C, 65 ± 5% RH)

	Sampling	**Measurement**	**Instrument**	**Reference**
Weight loss	Randomly selected and marked 10 fruit	Weight of the marked fruit were taken initially, after precooling and at 2 weeks intervals for 12 weeks and after 2 weeks of ambient storage	(Mettler Toledo, Model ML 3002E, Switzerland with 0.0001g accuracy)	
Color	The 10 fruit selected for weight loss measurement	The colour parameters in CIELAB coordinates (L*, a*, b*) of the pomegranate skin was taken initially (day 0), after precooling, and at 2 weeks intervals for 12 weeks in cold storage, and after ambient storage on two marked spots on each fruit surface	Minolta Chroma Meter (Model CR-400/410, Minolta Corp, Osaka, Japan),	Pathare *et al*. (2013)

Table 8.2 *Continued*

	Sampling	Measurement	Instrument	Reference
Decay	Visual inspection of all fruit	Fruit decay incidence was visually assessed on each sampling day. Fruit with external decay symptoms were counted. Percentage of fruit decayed was calculated as: [(number of fruit decayed/total number of fruit stored in each carton design)] × 100		
Total soluble solids	Juice was extracted from arils of 3 randomly selected pomegranate fruit packed in extra ND cartons	Drops of juice were placed on refractometer	Digital refractometer (Atago, Tokyo, Japan)	Fawole & Opara, (2013)
Respiration	Randomly selected 6 fruit	Fruit respiration was measured using a closed system. Two fruit were weighed and placed in airtight glass jars with rubber septum. Three jars were used each containing 2 fruit. Fruit were incubated for 2 h at the respective sampling conditions and then the gas composition inside each glass jar was measured. Carbon dioxide production was presented as mL CO_2 kg^{-1} h^{-1}	O_2/CO_2 analyser (PBI Dansensor CheckPoint, Ringsted, Denmark)	Caleb *et al.* (2012); Atukuri *et al.* (2017)

ND – new carton design.

8.5.2.2. Sensory evaluation

Quantitative descriptive sensory analysis was carried out on the pomegranate fruit at the end of the 2 weeks ambient storage period using a trained 10-member panel (4 women, 6 men) of the Postharvest Technology Research Group at Stellenbosch University who are familiar with the characteristics and taste of pomegranate fruit (Vázquez-Araújo *et al*. 2011; Chen & Opara, 2013; Atukuri *et al*., 2017). Pomegranate whole fruit and half cut sections were rated for color and overall appearance. The arils were rated for sweet taste, sour taste, off-flavor, and juiciness. The intensity of the attributes were rated on a scale of 0–4 (0 = none, 1 = slight, 2 = moderate, 3 = much, 4 = very much) (Atukuri *et al*., 2017). 'Herskowitz' is a sweet-sour pomegranate fruit cultivar with the sour taste being undesirable in extreme cases as can sometimes happen in some fruit.

8.5.3. Statistical analysis

Analysis of variance (ANOVA) was carried out using STATISTICA 13 (StatSoft, Inc. Oklahoma, USA). Means were separated using Duncan's multiple range tests (Factors: weight loss, Chroma, hue angle, total soluble solids and fruit respiration). Variations in weight loss, respiration and colour were compared between the package designs. Means with $p < 0.05$ were considered significant.

8.5.4. Quality test results

8.5.4.1. Fruit respiration

Fruit respiration followed a similar pattern in both carton designs with very minimal differences (Table 8.3). The respiration of the fruit in ND rapidly dropped from 15.89 ± 0.70 mL CO_2 l^{-1} kg^{-1} h^{-1} after precool to 5.66 ± 1.23 mL CO_2 l^{-1} kg^{-1} h^{-1} before remaining relatively constant throughout the 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% RH) at average 6.85 ± 0.16 mL CO_2 l^{-1} kg^{-1} h^{-1} (Table 8.3). At the end of the 2 weeks ambient storage period, fruit respiration increased close to 3 fold to 19.67 ± 0.71 mL CO_2 l^{-1} kg^{-1} h^{-1}. Caleb *et al*. (2012) reported respiration rate of 'Acco' and 'Herskowitz' pomegranate fruit in the range of 5.67–18.53 mL CO_2 l^{-1} kg^{-1} h^{-1} between 4–16 °C. This is similar to the respiration range observed in this study. The authors also reported that decreasing temperature from 15 to 5 °C reduced fruit respiration by 67%, a finding comparable to the 64% reduction in pomegranate fruit respiration upon precooling of the fruit from 20 to 7 °C in this study.

Pomegranate fruit are non-climacteric and are characterised by low respiration rates (Kader *et al*., 1984, Caleb *et al*., 2012; Arendse *et al*., 2015; Atukuri *et al*., 2017). Pomegranate fruit respiration increases with increase in storage temperature and duration (Fawole & Opara, 2013). This explains the rapid increase in fruit respiration within the shelf life period and the high initial fruit respiration before precooling. This may be triggered by fruit temperature stress, increased moisture loss, and microbial activity (Elyatem & Kader, 1984). 'Bhagwa' and 'Rubby' had respiratory rates between 4.5–7 mL CO_2 l^{-1} kg^{-1} h^{-1} over a 12 weeks storage period at 7 °C (Fawole & Opara, 2013). For the Wonderful cultivar, Kader *et al*. (1984) reported an average respiration rate of 8 mL CO_2 l^{-1} kg^{-1} h^{-1} for pomegranates stored between 0–10 °C for 12 weeks.

8.5.4.2. Weight loss of pomegranate fruit

Weight loss and associated fruit shrivel is one of the main pomegranate fruit quality loss mechanisms that affect the pomegranate fruit (Atukuri *et al*., 2017; Mukama *et al*., 2019) owing to a highly porous fruit peel (Elyatem & Kader, 1984). This loss in weight in fruit is largely a result of moisture loss. Pomegranate fruit was found to be more susceptible to weight loss compared to apples (Tu *et al*., 200; Mukama *et al*., 2019). Pomegranate fruit continuously lost weight throughout the cold storage period and in the shelf life period (Fig. 8.12). 3.8% and 6.2% cumulative weight loss was observed in the ND and CD, respectively, at the end of 12 weeks cold storage period (Fig. 8.12). This loss increased within the two weeks shelf life period to 5.7% and 8.9% in the ND and CD, respectively. This weight loss increase in the shelf life period corresponds with the observed increased respiration rate. Weight loss was relatively higher for fruit in the CD compared to the ND but generally followed a similar trend (Fig. 8.12).

Opara *et al*. (2008), reported weight losses of 3.85% in ‘Halow’ pomegranate stored at 7°C, 95% RH for 6 weeks, while Fawole and Opara (2013) reported weight loss between 15% and 17% for ‘Ruby’ and ‘Bhagwa’ pomegranate fruit cultivars stored at 7 °C for 12 weeks. For Wonderful cultivar, Arendese *et al*. (2014) reported 45% weight loss for fruit stored at 7.5 °C, 92% RH after 12 weeks of storage. These weight loss findings are relatively high compared to the 3.8% and 6.2% observed in this study. The difference could be because the authors did not mention using a polyliner in their fruit packaging which was used in the present study. Polyliners reduce moisture loss from fruit by maintaining a high relative humidity around packaged fruit (Mukama *et al*., 2019). Additionally, fruit in this study were coated with carnauba wax as one of the pack-house operations to minimise weight loss and extend the shelf life of the fruit (Muller, J.C., 2019, General Manager, Sonlia Pack-house, Wellington, South Africa, personal communication, 10 May).

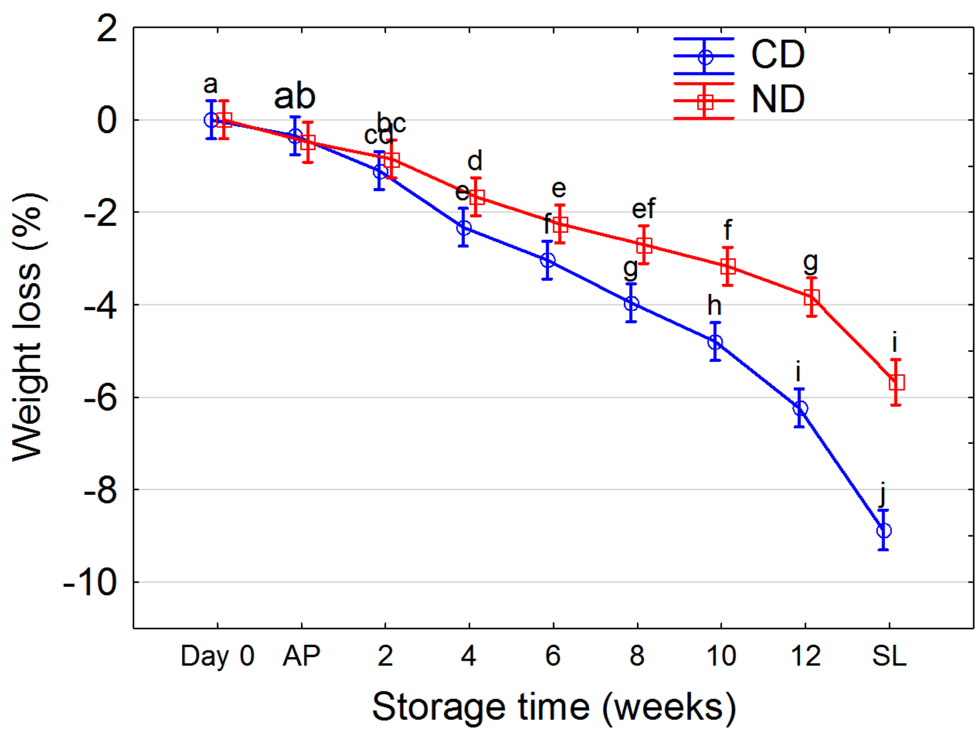


Fig. 8.12 Cumulative weight loss of pomegranate fruit (cv. Herskowitz) during 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% RH) and an additional 2 weeks at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH). AP – after precooling, SL – shelf life period. Vertical bars denote the standard error of 10 replicates. Means with different letters are significantly different ($p < 0.05$)

8.5.4.3. Fruit decay

There was no visible signs of decay in the fruit stored in the two carton designs until the 10th week of cold storage. Fruit decay, mainly starting from the fruit crown was observed from week 10, where one fruit (0.41%) was found decayed at the crown end in the commercial carton design (Fig. 8.13 (a)). Decay in pomegranates is caused by various pathogens including: *Aspergillus spp*, *Cladosporium spp*, *Colletotrichum spp*, *Epicoccum spp*, *Penicillium spp*, *Pestalotia* and *Botrytis cinerea* (Holland *et al*., 2009; Munhuweyi *et al*., 2016). Grey fungal growth around the calyx and crown area observed in this case is grey mould rot caused by *B. Cinerea* (Munhuweyi *et al*., 2016). This fungus has been reported to be the most economically important storage disease accounting for over 30% of fruit postharvest losses (Holland *et al*., 2009; Day & Wilkins, 2011; Munhuweyi *et al*., 2016).

At the end of the 12 weeks cold storage period, 7.5% of the fruit in the CD cartons had started showing signs of decay around the crown end (Fig 8.13 (a)), and 0.8% of the total fruit was fully decayed. Comparatively, in the ND cartons, 3.3% of the fruit total had started showing signs of fungal growth at the crown end, while 1.3% of the fruit was decayed. After the two weeks of ambient storage conditions, 0.4% of the fruit in the CD showed signs of start of mould growth around the crown, while 3.3% of the fruit was rotten; in the ND cartons, 5.8% of the total fruit was rotten at the end of the 2 weeks at ambient conditions. It is possible that the observed decay would be much lower had it not been for repeated opening of the polyliners of the stored fruit every fortnight for quality monitoring which may have predisposed fruit to fungal infections and destabilised the modified atmosphere created by the polyliner (18–19% O_2; 1% CO_2; 98% RH). Carbon dioxide enriched atmospheres are fungistatic (Day & Wilkins, 2011). The two carton designs generally had comparable fruit decay rates. The observed decay cases in this study (Fig. 8.13) could be categorised under (b) (*Penicillium spp*. 'blue mould fruit rot'), (c) (*Coniella granatai* fruit rot) and (d) (*Botrytis cinerea* 'greymould'), (Munoz *et al*., 2011; Munhuweyi *et al*., 2016). Fawole and Opara (2013) reported between 40–60% external disorders (external decay/scalding) for 'Bhagwa' and 'Ruby' pomegranate cultivars stored at 7 °C for 12 weeks. The comparatively high incidences of decay in that study could be because the fruit were not treated with postharvest fungicides and other pack-house treatments before storage.

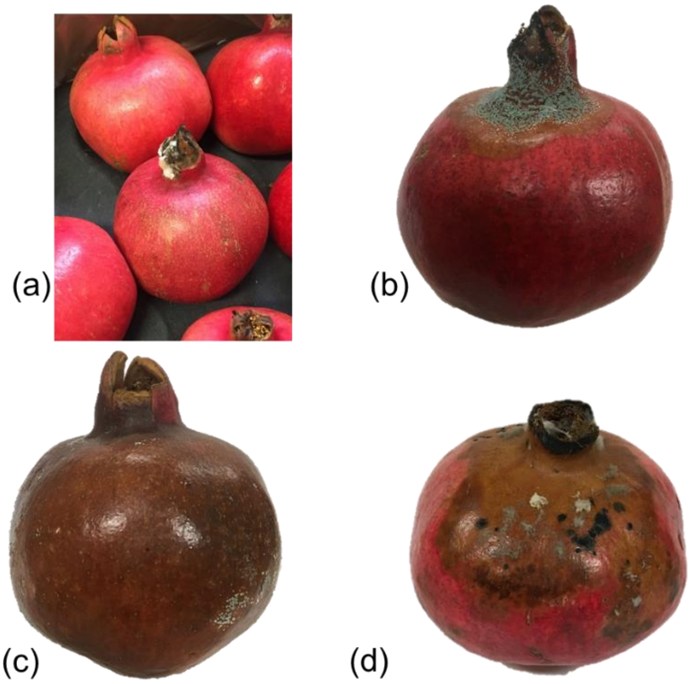


Fig. 8.13 Fruit decay observed in the 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% RH) and an additional 2 weeks storage period at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH) (a) fruit starting to show decay signs at the crown end, (b) (Penicillium spp. 'blue mould fruit rot'), (c) (Coniella granatai fruit rot), (d) (Botrytis cinerea 'grey mould fruit rot')

8.5.4.4. Fruit colour and Total soluble solids

The total colour difference (ΔE*), Chroma (C* 'colour intensity') and hue angle (h°) were calculated from the CIE L* a* b* values as in Eq. (8.1), Eq. (8.2), and Eq. (8.3), respectively. The hue angle is used to define the difference of a certain colour with reference to grey colour of the same lightness, while the Chroma determines the degree of difference of the hue (Pathare *et al*., 2013). The total colour difference gives the magnitude of the difference between the initial and final colour attributes (Martins & Silva 2002). The total colour difference can be classified as very distinct (ΔE > 3), distinct (1.5 < ΔE < 3), and small difference (1.5 < ΔE) (Adekunte *et al*. 2010; Pathare *et al*., 2013).

$$\Delta E * \sqrt{\Delta a *^2 + \Delta b *^2 + \Delta L *^2} \tag{8.1}$$

$$C * = \sqrt{a *^2 + b *^2} \tag{8.2}$$

$$h^\circ = tan^{-1}\left(\frac{b *}{a *}\right) \tag{8.3}$$

Generally, the Chroma of the pomegranate fruit reduced gradually throughout the storage period with a significant reduction in the Chroma recorded at the end of the shelf life period (Table 8.3). The change within the 12 weeks cold storage period was not significant in both carton designs. The fruit hue angle remained rather constant throughout the cold storage period and at the end of the 2 weeks shelf life period with no significant changes in the CD and ND cartons (Table 8.3). Fig. (8.14) shows the visual condition of the fruit and the fruit half cut sections throughout the storage period. The total colour difference was 2.5 and 2.1 for the ND and CD cartons at the end of the 12 weeks cold storage period, respectively. This indicates a 'distinct' colour difference (Pathare *et al*., 2013). After the two weeks ambient storage period, the total colour difference was 5.5 and 7.7 in the ND and CD cartons respectively indicating 'very distinct' colour difference in both designs. The observed total colour difference could be as a result of pigment breakdown due to increased fruit respiration at ambient storage conditions. Similar to our findings, the Chroma of Ruby, and Bhagwa pomegranate fruit cultivars reduced but not significantly over a 12 weeks storage period at 7 °C (Fawole & Opara, 2013). Arendse *et al*. (2014) also reported no significant changes in Chroma of pomegranate ('Wonderful') fruit stored at 7.5 °C, 92% RH over 12 weeks storage period, but observed a significant reduction after 16 and 20 weeks of storage.

Total soluble solids (TSS) of the fruit largely remained unchanged throughout the cold storage period until week 12 before a significant drop to 13.5 °brix after two weeks of ambient storage (Table 8.3). This observation also corresponds to the increased respiration in the shelf life period that breaks down the sugars in the fruit. For the Wonderful cultivar, Arendse *et al*. (2014, 2015) also observed no significant changes in TSS for 12 weeks at 7.5 °C, 92% RH, but, extending storage to 16 and 20 weeks at similar storage conditions caused a significant reduction in TSS from 15.84 °Brix at week 12 to 14.21 °Brix at the end of the 20th storage week.

Table 8.3 Changes in Total Soluble Solids (TSS), fruit respiration, Chroma (C*), and hue angle (h°) of pomegranate fruit (cv. Herskowitz) during 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% RH) and an additional 2 weeks at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH) in commercial carton (CD) and new carton design (ND). Values are means ± standard deviation. Means with different letters are significantly different ($p < 0.05$)

Storage Period	TSS (°Brix)	Respiration (mL CO_2 l^{-1} h^{-1})		C*		h°	
		ND	CD	ND	CD	ND	CD
Day 0	15.15 ± 0.07^{bc}	15.89 ± 0.70^{ab}	15.80 ± 0.65^{ab}	52.41 ± 2.01^{cd}	52.77 ± 2.07^{bcd}	27.93 ± 1.54^{abcd}	28.44 ± 2.75^{abcd}
After precooling	16.20 ± 0.71^{abc}	5.66 ± 0.23^{d}	5.65 ± 0.22^{d}	54.15 ± 2.22^{abc}	55.29 ± 2.50^{ab}	28.19 ± 1.63^{abcd}	28.99 ± 2.64^{abcd}
2 weeks	16.45 ± 0.49^{ab}	6.85 ± 0.68^{cd}	6.88 ± 0.58^{cd}	55.49 ± 2.19^{a}	54.20 ± 2.40^{abc}	28.48 ± 1.54^{abcd}	29.14 ± 2.63^{abc}
4 weeks	16.15 ± 0.49^{abc}	6.68 ± 0.83^{cd}	6.78 ± 0.03^{cd}	53.20 ± 2.63^{abcd}	52.89 ± 2.78^{abcd}	27.27 ± 2.23^{abcd}	29.31 ± 3.35^{abc}
6 weeks	17.45 ± 0.21^{a}	6.95 ± 0.40^{cd}	6.99 ± 0.30^{cd}	51.99 ± 2.28^{cd}	51.16 ± 2.83^{de}	26.92 ± 2.39^{bcd}	29.19 ± 3.54^{abc}
8 weeks	16.05 ± 1.06^{bc}	6.64 ± 0.02^{cd}	6.62 ± 0.02^{cd}	51.95 ± 2.65^{cd}	50.79 ± 2.92^{def}	27.58 ± 2.52^{abcd}	29.76 ± 3.84^{ab}
10 weeks	14.85 ± 0.49^{c}	6.92 ± 0.98^{cd}	6.96 ± 0.08^{cd}	48.74 ± 2.43^{efg}	48.39 ± 2.77^{fg}	26.79 ± 2.56^{bcd}	29.33 ± 3.89^{abc}
12 weeks	15.65 ± 0.07^{bc}	7.04 ± 0.54^{cd}	7.01 ± 0.51^{cd}	52.69 ± 3.03^{bcd}	50.82 ± 3.06^{def}	26.46 ± 2.43^{cd}	28.40 ± 3.78^{abcd}
Shelf life	13.50 ± 0.71^{d}	19.67 ± 0.71^{a}	19.57 ± 0.90^{a}	37.67 ± 2.89^{g}	45.35 ± 2.86^{h}	26.40 ± 3.35^{d}	30.31 ± 4.17^{a}

8.5.4.5. Sensory evaluation

Fruit stored in the ND and CD cartons scored high on colour attributes and overall appearance (OA) both for the whole fruit and fruit half cut sections (fruit-section) at the end of the shelf life storage period (Fig. 8.15 (a)). Comparatively, for colour of whole fruit and fruit-sections, the CD scored higher than the ND, while for overall appearance, of the whole fruit and fruit-sections, ND scored higher on fruit-sections while CD scored higher on whole fruit (Fig. 8.15 (a)). The arils of the fruit scored similarly on sweet and sour taste in both carton designs (Fig. 8.15 (b)). Arils in fruit in the CD design were juicier compared to the ND, while the fruit in both carton designs scored very low on off flavour (< 1) suggesting that the fruit generally remained fresh in the two carton designs at the end of the cold storage and additional shelf life storage period. The fruit scored higher for sweetness compared to sourness (Fig 8.15 (b)).

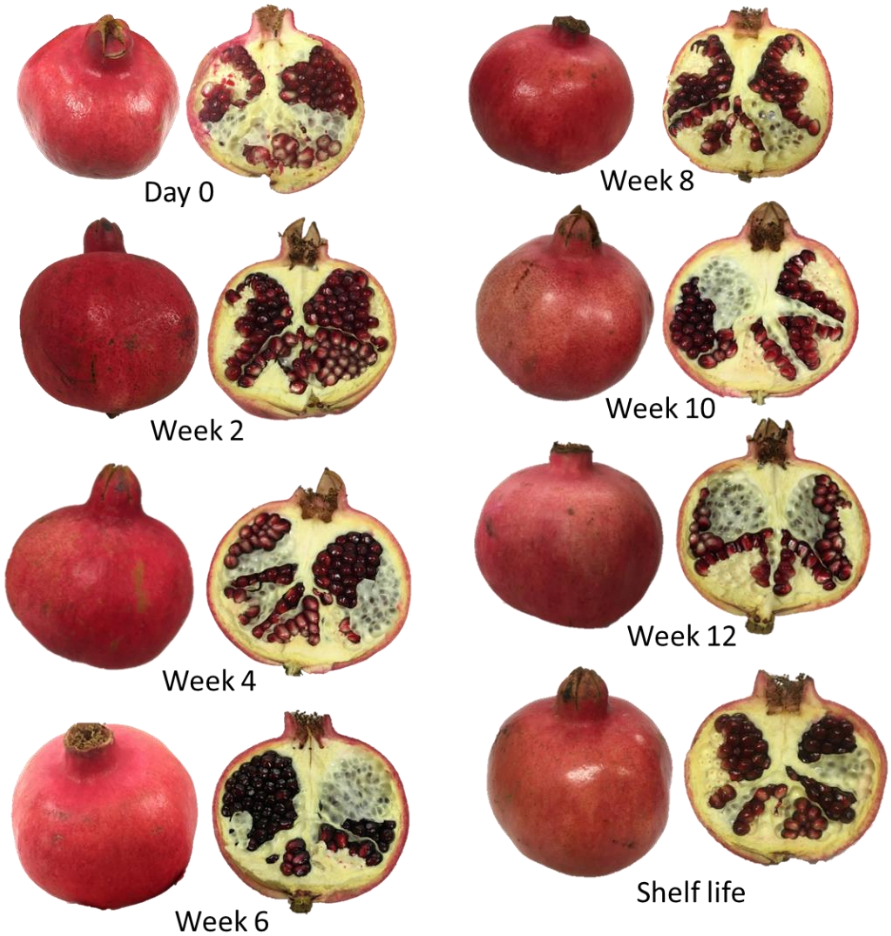
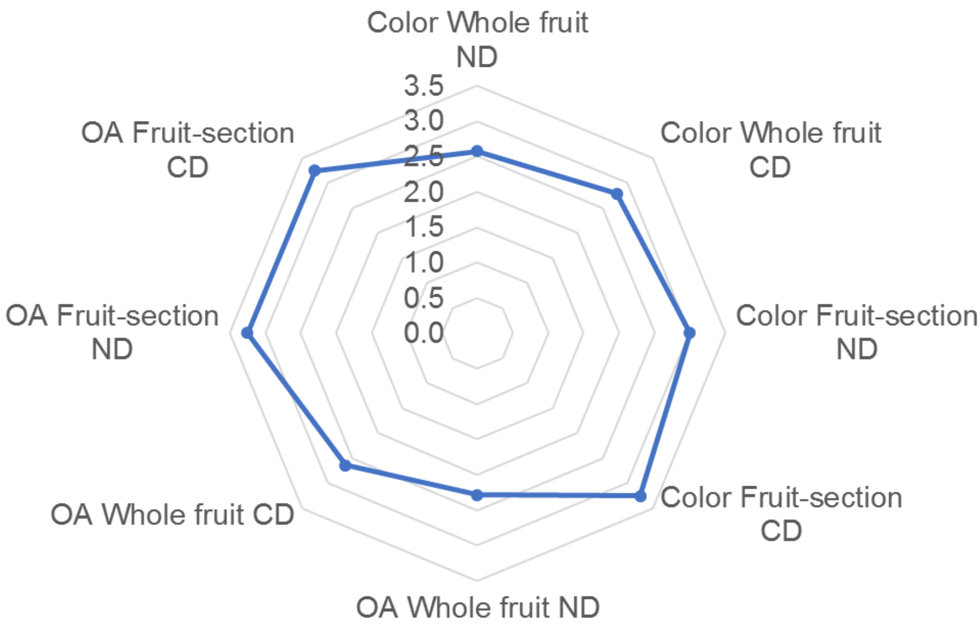
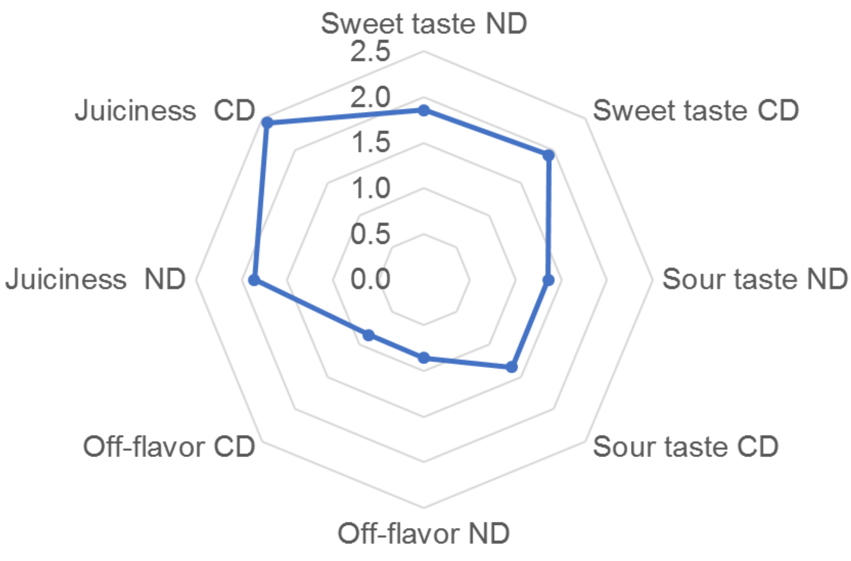


Fig. 8.14 Visual condition of pomegranate fruit and half fruit section from both commercial and new carton designs taken at 2 weeks intervals during a 12 weeks cold storage period (7 ± 1 °C; 90 ± 2% RH) and an additional 2 weeks at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH)



(a)



(b)

Fig. 8.15 Radar plot showing sensory scores of (a) whole pomegranate, and fruit half cut sections (fruit-section) and (b) arils of pomegranate fruit stored for 12 weeks under cold storage conditions (7 ± 1 °C; 90 ± 2% RH) and an additional 2 weeks at ambient conditions (shelf life; 20 ± 2 °C, 65 ± 5% RH) in commercial carton (CD) and new carton design (ND). Values are means of scores from 10 panellists. OA is overall appearance, scale: 0 = none, 1 = slight, 2 = moderate, 3 = much, 4 = very much

Arendse *et al*. (2015) observed a higher sweet and low acidic taste with increase in storage duration for pomegranate fruit (cv. Wonderful) after two months of cold storage attributing the decline in sour taste to the breakdown in organic acids required for the ongoing metabolism in the fruits during storage. The overall appearance, aril, and kernel texture also decreased. According to Mayuoni-Kirshinbaum *et al*. (2013) flavour preferences for arils derive mainly from sweetness and acidity. Arils high in sweetness and moderate to low acidity are highly preferred to sour and bitter arils.

8.6. Conclusion

Fruit quality drives the sensory and nutritional satisfaction, marketability, and profitability of fruit trade. Fruit cooled in the 'Midvent' carton with no liner cooled over 1 hour faster than in the 'Edgevent' and commercial carton design. Cooling heterogeneity was over 2-fold higher in liner packaged fruit compared to no-liner packaging in both carton designs. Storing cartons under cold conditions reduced carton compression strength by over 20% after 24 hours and a further 20% after 4 weeks due to weakening of paperboard cellulose fibres by the high relative humidity. The 'Midvent' carton design generally performed best in mechanical strength, remaining 15% above minimum compression force requirements after 4 weeks under cold storage. In a storage experiment assessing the quality of fruit stored in the 'Midvent' (new design—ND) vs commercial design (CD), pomegranate fruit quality attributes generally varied similarly in the CD and ND. The new design scored relatively better in weight loss reduction of fruit, 5.7% and 8.9% cumulative weight loss was observed in the ND and CD cartons, respectively at the end of the two weeks shelf life period. Fruit in both carton designs had similar respiration pattern marked by increases with increase in temperature. After the two weeks of ambient storage conditions, an average of 4.5% fruit was decayed in the CD and ND cartons. Fruit colour remained rather stable with no change in the h° in the two carton designs over the storage period. Therefore, commercialisation of the new carton design for pomegranate fruit handling is warranted to benefit from the increased handling volume, better cooling performance, and fruit quality protection.

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Chapter 9

General conclusion

Fruit are largely heterogeneous products with dissimilar physicochemical and biological properties. Therefore, to achieve ideal handling conditions for particular fruit or fruit groups, a focussed investigation is necessary. This study presents attempt to optimise ventilated packaging used in the fresh pomegranate fruit industry based on virtual prototyping and multiparameter analysis. An extensive review of literature (Chapter 2 and 4) highlighted limited scientific knowledge on the design of packaging used for cold chain handling of pomegranate fruit. Additionally, the thermophysical properties of pomegranate fruit were also largely unknown, yet they affect the design of cold chain handling systems including packaging and cooling. Therefore, to attempt to fill these gaps and address the study objectives, five research articles are presented in this study in chapter format. Chapter 3 determined the thermophysical properties of pomegranate fruit and parts relevant to the cold chain process Chapter 5 characterised the different packages used in the pomegranate industry, and Chapter 6 redesigned the ventilation of a commercial pomegranate fruit package. Additionally, Chapter 7 designed novel dual layer pomegranate carton designs with improved shipping density, and lastly, Chapter 8 evaluated the performance of the new designs and analysed the quality dynamics of fruit handled in the best of the new designs over a 12 weeks cold storage period and an additional 2 weeks ambient storage period. Findings and recommendations in these research chapters show that the aims and objectives set out in this study have been successfully achieved. Major contributions to knowledge reported in this thesis are summarised below.

The first key contribution of this study was the quantification of the thermal properties of whole pomegranate fruit (two cultivars) and its different fruit parts at different temperatures (Chapter 3). No previous study had extensively described pomegranate fruit thermal properties data to this extent. Thermal properties characterize the rate and degree of heat exchange between produce and its surrounding, and the data is a prerequisite for predicting heating or cooling rates, and to estimate heating or cooling loads of thermal processes. A transient heating probe system was used for accurate measurement of the specific heat capacity, thermal conductivity, and thermal diffusivity over a temperature range of (7 to 45) °C. The epicarp had significantly lower density compared to the mesocarp and arils. The aril part was observed to have the highest values of thermal conductivity and specific heat capacity. The values of thermal conductivity and diffusivity of the two pomegranate cultivars increased significantly with increase in tissue temperature and varied insignificantly between cultivars. The data generated in this study will aid future food processing decisions, design of equipment and processes for postharvest handling of pomegranate fruit in the effort to minimise loses and value addition. The data of the different parts forms a basis to model and predict the temperature transition across a single fruit and heat transfer in processing, for example, pomegranate juice pasteurisation.

The second contribution of this work was the identification and geometric characterisation of the different cartons and packaging modes applied in the pomegranate fruit industry. From the survey in Chapter 5, a number of different carton designs with different properties (dimensions, ventilations), and internal packaging modes, largely decided on by exporters and customers were found. This confirmed the lack of an objective design procedure backed by a multiparameter analysis, but rather subjective design decisions. The cartons were largely poorly ventilated on the short faces that led to poor carton vent-hole alignment and vent-hole blockage in stacking configurations that involve change of carton orientation (long side/short side) on the pallet. This increases the pressure drop, cooling time, and energy requirements of the packaged fruit cooling processes. The cartons used in the industry were also randomly named which created difficulty in the classification and identification of the different cartons in the industry. In this study, we suggested names for cartons with particular described characteristics in Chapter 5. The pomegranate industry can adopt this naming for future order. With technologies like pomegranate fruit waxing, future packaging may not need use of polyethylene liners given their negative effect on the environment and fruit cooling rates.

Another key contribution of this study was the implementation of a virtual prototyping approach based on computational fluid dynamics for redesign, testing, and improvement of carton designs. Virtual prototyping tools contribute to cost and time reduction in the design process. Such powerful modelling tools ride on the exponential growth of computer power that has eased the tedious and expensive nature of experiments. It also provides details that would be experimentally difficult, and the same tools can be used to predict future scenarios. Applying this approach to Chapter 6, a virtually tested improved carton with new vent-hole design was manufactured and experimentally tested. Fruit cooled in the new design had more uniform temperature distribution and significantly cooled faster. The new carton design also recorded lower pressure drop in the forced air cooling operation. By ensuring fairly unobstructed airflow in the stack of fruit during precooling, the performance of the fruit cooling process was significantly improved. Findings from this study concur with findings and recommendations from most previous studies that emphasize the need for proper ventilation, vent-hole alignment in stacks and avoidance of unnecessary internal packages that may act as barriers to airflow.

Futrther, the virtual prototyping design approach in Chapter 6 was applied in Chapter 7 to test different virtual design prototypes of different multilayer carton designs. The best designs were then evaluated for cold chain performance in Chapter 8. The virtual tools, computational fluid dynamics and computational solid dynamics were used to assess the airflow and mechanical performance of several virtual designs, with intent to design new fibreboard cartons that can cool pomegranate fruit faster and more uniformly, improve the fruit throughput and space utilization in the pomegranate fruit cold chain, especially shipping density, and could generally reduce material, energy, and handling costs. By running a virtual test, which took only few hours, it was possible to find an accurate measure of design parameters and detailed visualization of airflow contours and streamlines. The more fruit exporters can ship per refrigerated container, the lower the cost of transport, package requirements, labour, and this may ultimately lower the pomegranate fruit price on the market, which is rather comparatively high.

The new designs improved the throughput by over 1.8 tons more fruit in a reefer compared to tonnage in one of the studied commercial cartons. For a fully loaded 40-ft reefer, the new designs saved over 31% cardboard material and an estimated equivalent of 11 trees. Such findings that contribute to reduced resource utilisation and environmental strain are good news in the battle against climate change. One of the new designs (‘Midvent’) was also found to additionally, cool fruit at the fastest rate. This contributes to efforts to reduce energy demand of the forced air cooling process and increase fruit throughput during the peak season. One additional interesting finding in this study was that kraft paper grammage of 175K had the required strength for the whole pomegranate fruit cold chain handling process. This is cheaper than the 200K used for commercial cartons. This could thus be an additional cost saving avenue. Carton compression strength tests in this study were not only done at standard conditions (23 °C; 50% RH) like most previous studies, but the study also evaluated the cartons at cold storage conditions (7 °C; 92% RH), in a simulated refrigerated transport period (7 °C; 92% RH for 30 days), and the effect of fruit in the carton on the compression requirements. This approach provides holistic and more reliable data that explains the behaviour of the designs under the practical handling environment. This helps minimise discrepancies between laboratory and field performance tests.

Finaly, fulfilling all design requirements, especially strength, and performing best in precooling may not be enough indicators to determine suitability of a carton design to purpose; hence, Chapter 8 included monitoring of pomegranate fruit quality in the best performing novel dual layer carton, the 'Midvent'. Fruit undergo physical and chemical changes under storage, which are driven by storage conditions including packaging design. Fruit respiration followed a similar pattern in the new and tested commercial carton design, mainly affected by handling temperature, characterised by large drops on cooling the fruit. The commercial and new design cartons also showed similar fruit weight loss characteristics, decay, colour changes, and sensory properties. These findings warrant the commercialisation of the new dual design to benefit the pomegranate industry interms of increased export density, cooling efficiency, and space usage. A recent media release by cool logistics global indicated that there may be shortages of reefers required for export of fresh produce as early as 2020 (https://coollogisticsresources.com/global/). "*According to Thomas Eskesen, Founder of Eskesen Advisory, with orders of new reefer boxes well below the required 140,000 in the pipeline, the shortage of reefer boxes hitting the market early next year now seems almost a certainty. New orders currently stand at around 60,000, which is too low*." Given such circumstances, this study towards reduction in reefer requirements by the pomegranate industry and increased shipping density is absolutely timely.

Future research directions

The comprehensive multiparameter approach used in this study should shape future fruit packaging studies in order to have a holistic assessment of new and existing package designs to promote efficiency and productivity. This will result in the improvement of fruit cold chain handling efficiency and deal with the large postharvest loses, especially in developing conutries. Additionally, there is need to improve the ventilation of poorly ventilated current commercial cartons used in the pomegranate industry to improve their cooling efficiency. Given the current strain on energy requirements, it's only apparent that all processes are geared towards reduced energy demands and overall efficiency. It is worth mentioning that the new carton designs require to be tested for effect of vibrational, drop, and impact forces on fruit and package quality given that an additional layer of fruit has been added in the new packaging mode. To sum it all up, an export trial in the 'Midvent' carton is warranted. Fig. 9.1 shows a schematic of the study process towards achievement of study aim

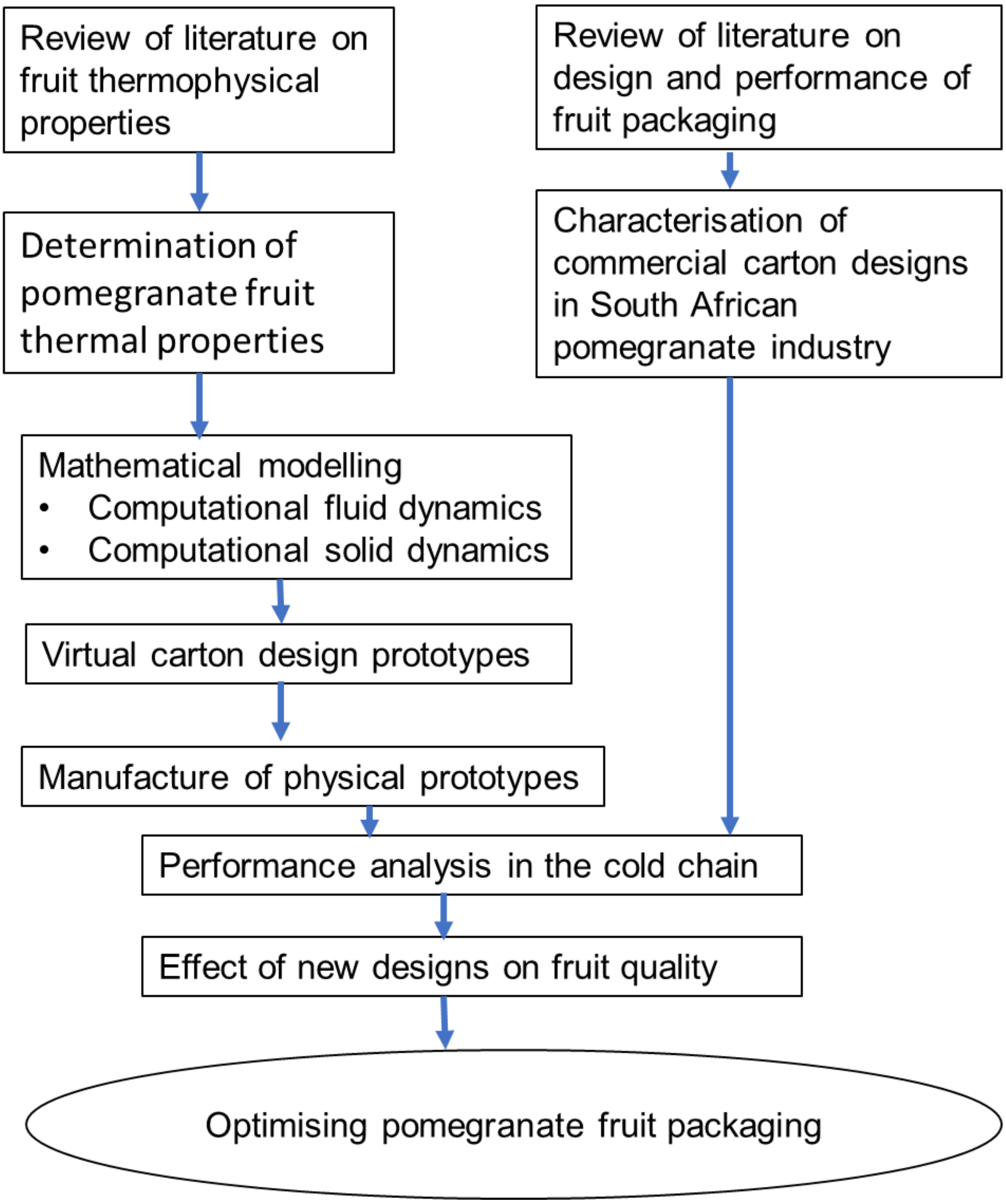

Fig. 9.1 Schematic of the study process towards achievement of study aim